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IMPROVED BOUNDS FOR ROW AGGREGATED LINEAR PROGRAMS:

A NOTE

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DRAFT FOR COMMENT

In [2], a result of Kallio [1] is extended in order to tighten Zipkin's [3] upper bound for column aggregated linear programs (LPs). In this note, it is shown that an identical procedure can be used to tighten Zipkin's lower bound for row aggregated LP's. The notation follows [3] throughout, and familiarity with the results and methods of [1, 2, 3] is assumed.

The primal LP to be solved is:

$$\begin{aligned} z^* = \text{maximize} \quad & cx \\ \text{subject to } & Ax \leq b \\ & x \geq 0 \end{aligned} \tag{1}$$

where $c = (c_j)$ is an n-vector, $b = (b_i)$ is an m-vector, $A = (a_{ij})$ is an $m \times n$ matrix, and $x = (x_j)$ is an n-vector of variables.

Let $\rho = \{R_\ell : \ell = 1, \ldots, L\}$ be a partition of $\{1, \ldots, m\}$, where $|R_\ell| = m_\ell$. Let f be a nonnegative m-vector whose components sum to unity. Define:

$$\tilde{b} = (\tilde{b}_\ell); \quad \tilde{b}_\ell = f^\ell b^\ell$$

$$\hat{A} = (\hat{a}_{kj}); \quad \hat{a}_{kl} = f^\ell A_\ell^k$$

so that the row aggregated LP becomes:

$$\begin{aligned} z = \max \; & cx \\ \text{subject to } & \hat{A}x \leq \tilde{b} \\ & x \geq 0 \end{aligned} \tag{2}$$

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For any partition $\rho' = \{R'_\ell : \ell = 1, \ldots, L'\}$, let $\{e_1 \ldots, e_m\}$ be known positive numbers, and $\{q_1, \ldots, q_{L'}\}$ known nonnegative numbers, such that u^*, the optimal dual variables in (1) satisfy:

$$\sum_{i \in R'_\ell} e_i u_i^* \leq q_\ell \quad , \quad \ell = 1, \ldots, L' \quad . \tag{3}$$

Then Zipkin [3] shows:

$$\hat{z} - \xi_\alpha^- \leq z^*$$

where $$\xi_\alpha^- = \sum_{\ell=1}^{L'} \left[\max_{i \in R'_\ell} \{(A_i \hat{x} - b_i)/e_i\} \right]^+ q_\ell$$

where $\hat{x}$ is an optimal solution to (2).

To extend theorem 2 in [1] and theorem 2.1 in [2], consider the dual to (1):

$$\begin{aligned} z^* = \text{minimize } & ub \\ \text{s.t. } & uA \geq c \\ & u \geq 0 \end{aligned} \tag{4}$$

transformed to:

$$\begin{aligned} \text{maximize } & u(-b) \\ \text{s.t. } & u(-A) \leq -c \\ & u \geq 0 \end{aligned} \tag{5}$$

The partition ρ and ρ', and the bounds (3) now apply to a column aggregated LP. The equivalent aggregate problem is:

$$\begin{aligned} &\text{maximize } U(-\tilde{b}) \\ &\text{s.t. } U(-\hat{A}) \leq -c \\ &U \geq 0 \end{aligned} \tag{6}$$

where U is an L-vector of variables. From proposition 2 in [3], and theorem 2.1 in [2], there exists a function $z(\theta)$, such that at θ^*,

$$\bar{u}(-b) \leq z(\theta^*) \leq \hat{U}(-\tilde{b}) + \xi_\alpha^- \tag{7}$$

This is equivalent to:

$$\hat{z} - \xi_\alpha^- \leq -z(\theta^*) \leq \bar{u}b = z^* \tag{8}$$

Equation (8) states that Kallio's method, as used to tighten the upper bounds on column aggregate problems, can also be used to tighten the lower bounds for a row aggregated problem. The reader is referred to [1] and theorem 2.1 in [2] for details of how to calculate $-z(\theta^*)$.

LITERATURE CITED

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[3] P. Zipkin. "Aggregation in linear programming." Ph.D. Dissertation, Yale University, New Haven, 189 p. (1977)

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Enclosed is a short companion to the earlier paper I sent you, "Improved bounds for aggregated linear programs." The purpose of the note was to convince myself that the method to improve upper bounds for column aggregated LP's does work for row aggregated LP's. Again, comments, suggestions, etc., are most welcome.

With regards,

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ALTERNATIVE ESTIMATES OF NET ECONOMIC BENEFITS FOR BILLFISH-TUNA RECREATIONAL-COMMERCIAL FISHERMEN IN KAILUA-KONA, HAWAII

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During 1976 about 1,500 trolling vessels were used primarily for weekend fishing trips in the Hawaiian Islands. About half of the weekend trolling fleet's total catch is tuna and a quarter is billfish. About 60% of the total catch is sold making the fleet one of the major suppliers of commercial fish in Hawaii.

An economic analysis of the weekend trolling fleet is prompted by the Fishery Conservation and Management Act of 1976 which extends Federal jurisdiction to 200 miles around the Hawaiian Islands. A typical question put by the public policymaker is what are the comparative effects on the nation's economic well-being of various possible management options. Billfish is one fishery in Hawaii to be managed.

Since participants of the weekend trolling fleet sell most of their catch and engage in fishing as a recreational activity they do not fit neatly into either economic role of consumer or producer. This dual role of the weekend fisherman has hampered the theoretical and empirical economic analysis for most fisheries with a fleet which cannot easily be divided into autonomous commercial and recreational components.

Measure of total net economic benefits. Net benefits are estimated for weekend fishermen using 386 vessels in Kailua-Kona during 1976. Net benefits are measured as the summation of consumer surplus and net revenue. Consumer surplus for the recreational-

commercial fisherman is defined as the difference between what the individual is willing to pay for different quantitites of a good and what he actually pays. If the marginal utility of money is constant consumer surplus may be measured as the area between the demand curve and the price line.[1]

Net revenue is based on revenue from the sale of fish and the cost of the fishing trips attributed to the fisherman's choice to make some commercial sales.

Specification of the recreational-commercial demand model. The demand model is estimated as an exponential function in the form

$$(1) \qquad \ln T_i = \beta_0 + \beta_1 P_i + \beta_2 V_i + \beta_3 C_i + \beta_4 Y_i + \varepsilon_i$$

where

T_i number of annual passenger trips for the ith vessel during 1976

P_i operating (average variable) cost per passenger trip for the ith vessel

V_i current value of the ith vessel and gear

C_i kilograms of fish caught per passenger trip for the ith vessel

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[1]For more details on consumer surplus see A. Marshall, Principles of Economics, 9th edition, The MacMillan Company, New York, 1961; J. M. Hicks, "The Four Consumer's Surpluses," Review of Economic Studies, vol. 12, 1944; and, A. M. Henderson, "Consumer's Surplus and the Compensating Variation," Review of Economic Studies, vol. 8, 1941.

Y_i annual income for the owner of the ith vessel

ε_i disturbance term

Leisure time is an important explanatory variable for recreational demand that is not specified in the model due to the absence of data. However, since most of the fishermen have full-time jobs the sample is likely to be relatively homogeneous with respect to leisure time. Other variables are included as the model is further developed.

Estimation of the models and alternative measures of net benefits. Preliminary estimates of the initial model revealed heteroscedastic problems in the survey data. Therefore a generalized least squares estimating procedure is used to estimate the models. Table 1 gives the results of five models in the untransformed versions.

Model I follows from the original specifications described above which treats the weekend trolling fleet as strict recreationalists. Evaluating the estimated equation at the mean values for all the independent variables except P yields the demand function

$$T = e^{4.308 - 0.017P} \tag{2}$$

It is assumed that the average vessel is used for at least one trip per year. Therefore, for levels of passenger trip demand less than the average number of passengers per trip, 2.56, demand is assumed to be perfectly elastic. Solving for P defines the upper bound of the

Table 1.—Regression coefficients, t-statistics, F-tests, and goodness-of-fit measures in regression equations to explain the natural logarithm of passenger trips taken by a vessel (LT) in Kailua-Kona, Hawaii during 1976 using cross-sectional observations.**

Model	No. of observations (n)	Independent variable											
		CONSTANT	P	V	C	$Y^{\hat{\delta}/2}$**	D_1	D_2	D_3	PD_3	I	R^{2***}	F
I	114	4.27 *	-.02 *	.27E-4 *	.004	-2.02						.50	26.94
		(8.75)	(-2.60)	(2.44)	(.47)	(-.31)							
II	114	3.87 *	-.02 *	.30E-4 *	-.02	-1.01	.26	.81 *				.62	29.12
		(8.95)	(-2.84)	(3.09)	(-1.94)	(-.18)	(.79)	(5.86)					
III	49	3.96 *	-.02 *	.24E-4 *	.001	-12.90			.25			.79	32.12
		(10.87)	(-2.92)	(2.36)	(.06)	(-.32)			(.73)				
IV	114	3.91 *	-.02 *	.32E-4 *	-.007	-.67			.61*	.0009		.61	28.45
		(9.00)	(-2.70)	(3.20)	(-1.76)	(-.11)			(3.26)	(1.15)			
V	114	4.14 *	-.02 *	.29E-4 *	-.004	-3.54					.47 *	.60	32.66
		(9.49)	(-2.93)	(2.89)	-1.07)	(-.61)					(5.33)		

Number of observations	Estimated heteroscedastic parameter ($\hat{\delta}$)**and t-statistic
114	-.56
	(-1.59)
49	-1.00
	(-1.88)

* coefficient is significantly different from zero at the 95% level (two-tail test)

**The regression results are on the transformed model for a weighted least squares regression using $Y_i^{\hat{\delta}/2}$, i = 1,..., n, as the weights obtained by regressing $(\hat{LT}_i - LT_i)^2$, from an ordinary least squares regression, against $Y_i^{\delta}e^{\rho}$ where ρ is a homoscedastic error term for the regression equation in logarithmic form. Using the independent variables other than Y to estimate the error variances results in heteroscedastic parameters which are not significantly different from zero at the 90% level.

***Not corrected for generalized least squares estimation procedures.

price range. Average variable cost defines the lower bound of the price range when measuring consumer surplus. Evaluating the integral of Eq. (2) for the interval P = [11.40, 198.52], the measure of consumer surplus for an average vessel is $3,554. Since costs are considered in the measure of consumer surplus, the gross revenue from the sale of fish is considered as additional net benefits amounting to $688 per year for an average vessel. Total net benefits for a vessel using this method, then, amount to $4,242, or $1,637,412 for the fleet of 386 vessels in Kailua-Kona during 1976.

This approach ignores the fact that at least some of the trips were prompted by the fleet's ability to sell some of its catch. But from Model I it is not possible to discern the number of additional trips. It is likely, though, that the above estimate for the fleet is an overestimate due to the resulting double counting. On the surface, however, the measure seems intuitively appealing from an economic standpoint since the total measure is close to determining a larger consumer surplus after reducing the price by the average revenue generated per passenger trip.

Model III is one possible approach of improving on the first measure of net benefits by dividing the fleet into individual recreational and commercial components. In this model only vessels selling less than 17% of their catch are analyzed based on the results of Model II where

D_1 equals 1 if the weight sold is less than or equal to 17% of total weight caught; equals zero otherwise

D_2 equals 1 if the weight sold is greater than 17% of total weight caught; equals zero otherwise

D_3 equals 1 if any of the catch is sold; equals zero otherwise

The results of Model II indicate that for the component of fishermen who sell their catch, those selling 17% or less do not behave significantly different than the component selling no fish at all. But those selling more than 17% of their total catch appear to take more trips which may be attributed to their ability to sell the catch which is in excess of the fish they demand for home consumption or gifts.

Assuming, then, that the fleet may be divided into recreational and commercial components, the following demand function may be derived from Model III to estimate the consumer surplus for the recreational component of the fleet.

$$T = e^{4.016 - 0.025P} \tag{3}$$

The demand function for an average vessel is representative for about 166 vessels in Kailua-Kona during 1976. Evaluating the integral of Eq. (3) for the interval P = [10.94, 124.95], the estimated consumer surplus is $1,620, which yields $268,920 for the 166 vessels.

The other 220 vessels in the fleet are treated strictly as commercial vessels which show a negative total net revenue of -$1,415. The combined measure of net benefits for the recreation and commercial components of the fleet total $267,505.

This second alternative measure of net benefits for the total fleet appears to be low since it is unlikely that the entrepreneurs of the commercial component would remain in the fishery with returns close to zero. Furthermore, even though the intercept dummy variable, D_2 in Model II, indicates a difference in the groups attributed to the ability to sell an excess catch, there is another important behavioral variable which indicates the two groups are not so different. Model IV introduces a new variable, PD_3, the product of P and D_3 which assumes that the commercial component responds differently to changes in average variable cost than the component which does not sell its catch. The results of estimating Model IV using the slope dummy variable indicate that the respective coefficient is not significantly different from zero. Under usual conditions a firm's output is inversely related to costs, but it is not clear that this is an appropriate interpretation for a weekend fishery with participants who have other full-time occupations. The fact that the demand slopes of the two proposed components of the fleet are not significantly different creates more serious questions about treating the components as mutually exclusive in the analysis. The fact that the commercial component just breaks even suggests

that there are benefits not being measured and that this second alternative measure underestimates net benefits for the total fleet.

Model V, then, treats the fleet as a single group with some fishermen selling a part of their catch. In the previous models, the average fisherman will continue to take more trips during a given year until the value of the last trip is equal to the cost of the same trip. That is the recreational fisherman will continue fishing until the marginal value is equal to the price of fishing. The fisherman will take additional trips only if he can accrue benefits in addition to the existing recreational benefits. The fact that fishermen can sell part of their catch in Kailua-Kona prompts many to take additional trips. These decisions may be reflected in the length of a day's trip, number of trips per week, month, or year. But additional trips for an average vessel which are prompted by commercial sales should be attributed to commercial motivations--not measured as additional recreational benefits as in the first alternative measure of net benefits. And also, the recreational benefits which accrue to fishermen should not be deleted just because a part of the catch is sold as in the second alternative measure of net benefits.

The commercial motivation edging the weekend recreational fisherman can be measured by a number of variables. One variable is certainly the price of fish. The price of fresh fish in Hawaii is relatively volatile due to large fluctuations in seasonal consumer

demand. It is likely that a recreational-commercial fisherman will respond differently to a fish price change based on the proportion of total catch sold. A relative index is desirable since the quantity of fish usable for home consumption and donations may vary widely for different fishermen. Therefore the variable I is introduced which is an index of relative excess landings for consumption and donations weighted by the average value of sales for the year. The demand curve estimated from Model V is

$$T = e^{4.316 - 0.017P} \tag{4}$$

The average elasticity of demand with respect to I is 0.40. For those fishermen who sell none of their catch, a change in the ex-vessel price of fish will not influence the number of trips they take. But for those fishermen who do sell some of their catch, the larger the excess catch, the more sensitive will be the change in demand due to a change in fish prices. Setting I equal to zero, then, shifts the demand curve such that

$$T = e^{3.975 - 0.017P} \tag{5}$$

Evaluating the integral of Eq. (5) for the interval P = [11.40, 177.27] yields $2,410 for the vessel and $930,260 for the fleet in recreational consumer surplus. Net revenue received for the additional trips

prompted by commercial incentives amounts to $187,210, yielding a total net benefit for the fleet of $1,117,470.

This third alternative measure of net benefits is less than the first measure, $1,637,412, which considered all members of the fleet recreationalists, and it is greater than the second measure, $267,505, which divided the fleet into autonomous recreational and commercial components.

Possible areas of application for public policy issues. The results of the final model indicate that recreational demand is insensitive to incremental changes in the catch rate. That is the estimated coefficient for the variable C is not significantly different from zero. For the fleet analyzed here the only change in net benefits, attributed to a policy which may change the catch rate, will be due to changes in net revenue from the sale of fish.

Policy alternatives which include overall quotas, quota allocations to various user groups, limited fishing days per year, or bag limits may be analyzed by estimating net benefits by passenger-day trip or by quantity of fish based on the results of the analysis.

ASSESSMENT OF THE ARMORHEAD STOCK ON THE MID-PACIFIC SEAMOUNTS

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This is a background document prepared for the Western Pacific Regional Fishery Management Council Seamount Resources Planning Team. It will not be published in the present form and should not be cited in the literature.

Stock Identity

The first task in assessing the armorhead resource is to come to some judgment on stock structure and identity. If the stock and fishery dynamics on the Hancock Seamounts are independent of events occurring elsewhere, then the Hancock armorheads can be treated as a unit stock. Stock assessment can then be attempted using data on the catch and effort history of just the Hancock Seamounts fishery, and a rational management policy can be developed without necessarily considering activities on other seamounts in the region. On the other hand, if the armorheads on Hancock are from the same stock as those exploited further out on the seamount chain, the stock assessment must be based on catch statistics representing the entire range of the fishery, and the policy analysis will have to consider the implications of fishing outside the Fishery Conservation Zone (FCZ).

At this juncture it must be pointed out that two "types" of armorhead are recognized, a "fat type" with a relatively deep body and the blue-over-white coloration typical of many surface swimming fishes, and a "lean type" with a much shallower body and uniformly gray coloration. The two types tend to occupy different habitats--the fat form inhabiting the surface waters of the northeastern Pacific and the lean type being associated with the seamounts of the central North Pacific. Some of the fat type armorheads also occur on the seamounts, but lean fish usually predominate there. Armorhead catches by the Ryoyo Maru No. 2 in April-June 1978, were essentially 100% lean type

on Hancock and Kinmei Seamounts, although 37% of the armorheads sampled from catches on the Colahan Seamounts were of the fat type (Kazama 1978). Even among lean fish there are a variety of forms; the Hancock Seamounts are noted for a relatively high proportion of "very lean" armorheads, brownish in color, elongate and with a very thin and delicate skin.

Whether this wide range in form represents genetic polymorphism in the species or is a result of differences in habitat and environmental factors alone remains to be determined. If there is just one integral stock of armorheads in the entire North Pacific, then we have no basis for assessing it, since the seamount fishery covers only a tiny part of the whole range. We assume hereafter that the "fat type" and "lean type" fish are from different stocks, and that the armorheads on the Hancock Seamounts inside the FCZ are members of a single stock of lean armorheads occupying the entire seamount chain (the presence of fat type armorheads on some of the seamounts is assumed of negligible consequence).

There is a considerable body of evidence sustaining the idea of a single, homogeneous stock on the seamounts. Specifically,

(1) The species has pelagic, free-floating eggs and larvae, so that a considerable degree of intermingling of offspring from adults inhabiting closely adjacent seamounts is likely;

(2) Catch rates of Japanese trawlers operating on the Hancock Seamounts during the period 1969-76 are virtually identical to the aggregate catch rates experienced by the same fleet over the entire range of seamounts. Density of armorheads in any given year appears to be

similar on the different seamounts, and annual variations in density tend to follow the same pattern;

(3) The size composition of armorhead catches in the Japanese trawl fishery is the same on all seamounts in the range.

Although these observations certainly support a common-stock hypothesis, it is not clear what factors govern recruitment or occupation of the seamount habitats by armorheads. Nor is it understood why the stock density would be so nearly the same on Hancock as on the other seamounts.

Index of Abundance

Assuming a single stock of armorheads on the seamount chain, we can construct an index of stock abundance using the aggregate catch per unit effort statistics of the Japanese trawling fleet. Table 1 shows the annual sequence of catch rates from 1969, when the Japanese fishery began, through 1976. According to Takahashi and Sasaki (1977), the first 3 years were developmental in nature, and it was not until 1972 that the fleet's operations stabilized. From 1972 through 1976 the total Japanese armorhead catch has ranged between 18,950 metric tons (MT) and 34,450 MT, while effort has increased from 550 h of trawling to 2,670 h. The average catch rate over the 5-yr period has dropped steadily from 60.2 MT/h to only 9.7 MT/h.

The steady decline in the index of abundance over 1972-76 may be due to a number of plausible factors, including (1) declining trend in recruitment, (2) increasing fishing mortality rate, or (3) declining trend in availability of armorheads on the seamounts. The first factor

would involve an actual decrease in the number of armorheads reaching the minimum harvestable age (about 3-4 yr), whether due to decreased egg production in the preceding years or increased natural mortality of pre-recruits. [The reduction in egg production might in turn be caused by high fishing mortality on mature armorheads.] The second factor, given constant recruitment, involves progressively fewer armorheads being caught in the older age groups relative to the harvest of younger recruited fish, and a general reduction in the average abundance of exploitable armorheads. The third factor implies some process whereby seamounts, as only one of several possible habitats, are occupied by armorheads of harvestable size periodically, and the fraction of the stock actually occurring there, available to the trawlers, varies from year to year.

To determine which one of these factors (or which combination) might underlie the declining index of abundance, one must examine other data. Some insight is provided by the information on fishing effort and size composition of the catch. The increasing effort trend (Table 1) suggests a corresponding increase in fishing mortality rate, providing availability did not decrease substantially during the period. On the other hand, an increase in fishing mortality rate is inconsistent with the observed shift in the length composition of armorheads (Figure 1) between 1972 and 1976. Rather than a shift toward small fish, there was apparently a trend toward larger armorheads in the trawl catches. This would suggest perhaps a decrease in fishing mortality rate (assuming constant recruitment), which might result from a sharp decline in availability. Such a fall-off

in availability would also explain the reduction in the abundance index. Another possibility is that the increase in fishing effort did indeed produce a corresponding rise in the fishing mortality rate, and that the changes in length composition of armorhead catches were a result of a pulse increase in recruitment in 1972. Still another possible explanation of shifts in the size distribution would be variable influxes of "fat type" armorheads into the population of predominantly "lean type" fish. An increase in the relative abundance of fat fish would tend to shift the distribution downward, and vice versa. Clearly there are many permutations of assumptions which would be compatible with the meager observations at hand.

Total Catch and Total Effort

Two nations have participated in the seamount trawl fishery on mid-Pacific seamounts--Japan and the U.S.S.R. Japanese catches of armorhead and alfonsin are given in Table 2 after Takahashi and Sasaki (1977). They are not reported in the 1976 Yearbook of Fishery Statistics published by FAO. On the other hand, the Soviet catches of alfonsin are reported in the FAO Yearbook, but armorhead catches are not given and no other source of U.S.S.R. catch data is available.

le 2

To estimate the total armorhead catch, we could compute the ratio of Soviet alfonsin catch to Japanese alfonsin catch on the seamounts and then simply expand the Japanese armorhead catch statistics, assuming the same species composition in the catches. But the resulting ratio is about 16:1, and the projected Soviet armorhead catch is

unreasonably large. Thus there is no available estimate of the total catch of armorheads, and no available estimate of total effective effort on the armorhead stock that can be supported statistically.

In the production model analyses described below, it was assumed that the Soviet armorhead catch each year, 1972-76, was equal to the Japanese catch. Total effective fishing effort was then computed be dividing the estimated total catch in a given year by the corresponding index of abundance. The assumption on the Soviet catch probably puts the total catch at the correct order of magnitude, at least. In the analysis, whether the Soviet and Japanese catches are equal is not important so long as the ratio between them is the same each year.

Production Model Analysis and Estimates of Maximum Sustainable Yield

A surplus production model (Schaefer model) was used to estimate maximum sustainable yield (MSY) and the associated optimum fishing effort (EOPT) for the seamount armorhead stock. The model assumes that the reduction in the index of stock abundance was a linear function of increased fishing effort, and that recruitment and availability were constant over 1972-76. It ignores information on length composition.

The model is an equilibrium yield model, whereas the raw data represent transitional states in stock size and effort. The Gulland method of effort-averaging was used to approximate equilibrium conditions. The average effort in a given year was computed as the mean of the actual effort in that year and the actual effort of the preceding year. As a result of the effort averaging, only four data points remained for the analysis, 1973-76. For purposes of comparison, the production

model was also fit to the full data set, i.e., the five pairs of catch rate and actual effort.

Results of the production model analysis are given in
gs. 2, 3 Figures 2 and 3. Figure 2 presents the relationship between the index of abundance and the averaged and unaveraged measures of effective effort, and the fitted regression lines. Figure 3 shows the resulting yield-effort curves. The estimated MSY is 76,500 MT of armorheads in the case of unaveraged effort, and 52,600 MT when the smoothed effort statistics are used. Corresponding optimum fishing effort estimates are 2,800 and 2,400 trawling hours. Because the effort averaging presumably corrects for nonequilibrium biases which result when the actual annual catch and effort statistics are used, the best estimates for MSY and EOPT are here assumed to be 52,600 MT and 2,400 trawling hours. This effort figure was exceeded in 1975 and 1976 (Table 1).

These estimates of armorhead MSY and optimum effort refer to the hypothesized single stock occupying the entire mid-Pacific seamount range. Further, the analysis assumed the Soviet catches were equal to the Japanese harvests each year. If the latter assumption is incorrect, the production model analysis is still useful so long as there is no change in the ratio of Soviet to Japanese catch over the years. Suppose this ratio is θ. Then the standard estimates of MSY and optimum effort (given above) can easily be adjusted according to the formulas:

$$\text{Adjusted MSY} = \left(\text{Standard MSY}\right)\left(\frac{1+\theta}{2}\right)$$

and $$\text{Adjusted EOPT} = \left(\text{Standard EOPT}\right)\left(\frac{1+\theta}{2}\right) \quad .$$

If θ is not constant from year to year, the production model analysis given here is invalid. It would have to be repeated using the complete records of Japanese and Soviet catch.

How about the effects of other assumptions? Not much can be said about availability without independent information on stock size and distribution. But concerning recruitment, if we assume there was a pulse increase in recruitment in 1972 (consistent with observed shifts in length composition), then the production model analysis is probably conservative. That is, the impact of fishing effort on the abundance index is not as great as the model suggests and recent effort levels may actually be less than EOPT.

Optimum Yield, Domestic Capacity and Total Allowable Level of Foreign Fishing

The Fishery Conservation and Management Act (FCMA) requires that a Fishery Management Plan (FMP) specify the optimum yield (OY) for each species under consideration, compute the expected domestic catch capacity, and determine the surplus (if any) available for harvest by foreign fleets. There are serious conceptual difficulties in the case of armorheads, akin to the problems faced in the Pacific billfish FMP. Our basic assumption is that armorheads are essentially

"highly migratory," or at least that only a small part of the stock occupies habitat within our FCZ and is subject to our direct control. This severely conditions the "optimality" of our yield policy, and alters the usual list of management policy considerations.

Putting this problem aside, a variety of criteria may be applied to evaluate alternative policies and to help define an optimal one. These might include:

(1) Maximize armorhead harvest subject to biological productivity constraints. For example, encourage more fishing, but make sure the total fishing effort does not exceed the level, EOPT, producing the MSY.

(2) Ensure continued collection of data for stock assessment. Since the catch rates on the Hancock Seamounts provide an index of the entire stock's abundance, a reasonable amount of foreign fishing on Hancock would be valuable.

(3) Maximize profit potentials for U.S. vessels wishing to exploit the armorhead stock. Maintain stock size at high levels, allowing prospective domestic fishermen to enter the fishery with relatively high catch rates.

(4) Protect other seamount resources of value to the U.S., such as precious coral, which may be taken inadvertently in the course of trawling.

This list could easily be extended, but it states most of the key management objectives. How are the criteria affected by the peculiarities of the armorhead resource? Certainly objective (1) will be

impossible to achieve solely by U.S. action; only a small fraction of the stock is inside the FCZ and only part of the catch is taken there. Virtually nothing can be done unilaterally by the U.S. to ensure that EOPT is not exceeded. The same goes for the third objective. Because the stock is exposed to fishing outside the FCZ, the stock size and hence catch rates are determined by factors outside U.S. control. In terms of our ability to establish effective management policy, only criteria (2) and (4) seem to be meaningful. A reasonable policy with respect to foreign fishing would therefore be to:

(1) Encourage foreign armorhead trawling at levels established in recent years (i.e., about 2,000 MT/yr), and collect detailed data on the catch, effort, and other aspects of the fishing activity,

(2) Establish guidelines for the incidental take of coral and other species of value to the U.S.

(3) Promote the careful assessment of the armorhead stock over its entire range and draw attention to the need for international management action if the health of the stock is threatened.

Assuming this would be the "optimum policy," then the associated optimum yield is

$$OY = 2{,}000 \text{ MT/yr}$$

Apparently there is no immediate U.S. interest in harvesting armorhead, so we can assume the domestic annual harvest will be zero. This leaves us with a Total Allowable Level of Foreign Fishing (TALFF) equal to the OY, or

$$TALFF = 2{,}000 \text{ MT/yr}$$

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Table 1.--Catch and effort statistics used in assessing the armorhead stock. Total effort and catch assumes Soviet catch equal to Japanese catch.

Year	Observed			Assumed total effort		Assumed total catch	
	Japan catch (10^3 MT)	Japan effort (10^3 h)	Japan C/E (MT/h)	1-yr (10^3 h)	2-yr (10^3 h)	1-yr (10^3 MT)	2-yr (10^3 MT)
1969	8.28	0.16	20.9	--	--	--	--
1970	30.05	2.81	10.7	--	--	--	--
1971	5.89	1.30	4.5	--	--	--	--
1972	29.88	0.50	60.2	1.00	--	59.76	--
1973	25.05	0.74	33.8	1.48	1.24	50.10	41.78
1974	34.54	1.59	21.8	3.18	2.33	69.08	50.75
1975	18.95	1.38	13.8	2.76	2.96	37.90	40.92
1976	25.80	2.67	9.7	5.34	4.04	51.60	39.23

Table 2.--Japanese trawling effort and associated catches of armorhead over the central North Pacific seamounts and over the Hancock Seamounts, and the percentage of catch and effort expended on Hancock in relation to the total seamount area.

Year	All central North Pacific seamounts (including Hancock)			Hancock Seamounts			Percentage of catch and effort on Hancock Seamounts	
	Catch (MT)	Effort (h)	C/E (MT/h)	Catch (MT)	Effort (h)	C/E (MT/h)	Catch (%)	Effort (%)
1969	8,280	157	20.892	--	--	--	--	--
1970	30,047	2,807	10.704	180	17	10.588	0.6	0.6
1971	5,891	1,304	4.525	221	51	4.333	3.8	3.9
1972	29,880	496	60.242	1,994	24	83.083	6.7	4.8
1973	25,047	740	33.847	8,518	212	40.179	34.0	28.6
1974	34,538	1,588	21.818	1,744	75	23.253	5.0	4.7
1975	18,952	1,377	13.763	653	42	15.548	3.4	3.0
1976	25,795	2,667	9.672	1,112	101	11.010	4.3	3.8

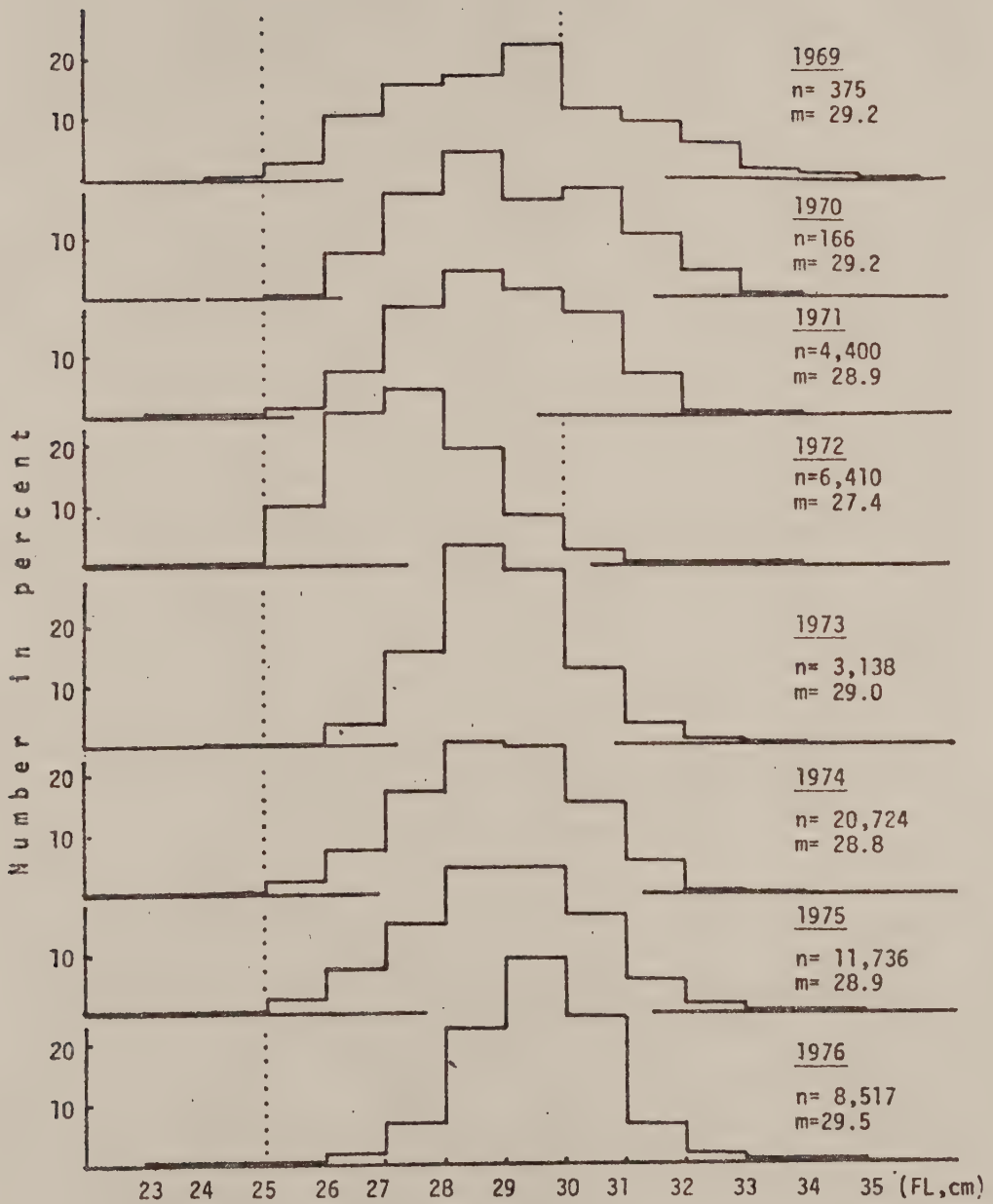


Fig. 1 - The fork - length composition of armorhead in th trawl fishery on the central North Pacific Seamounts, 1969-76.
n: number of individuals sampled. m: average fork-length (cm)

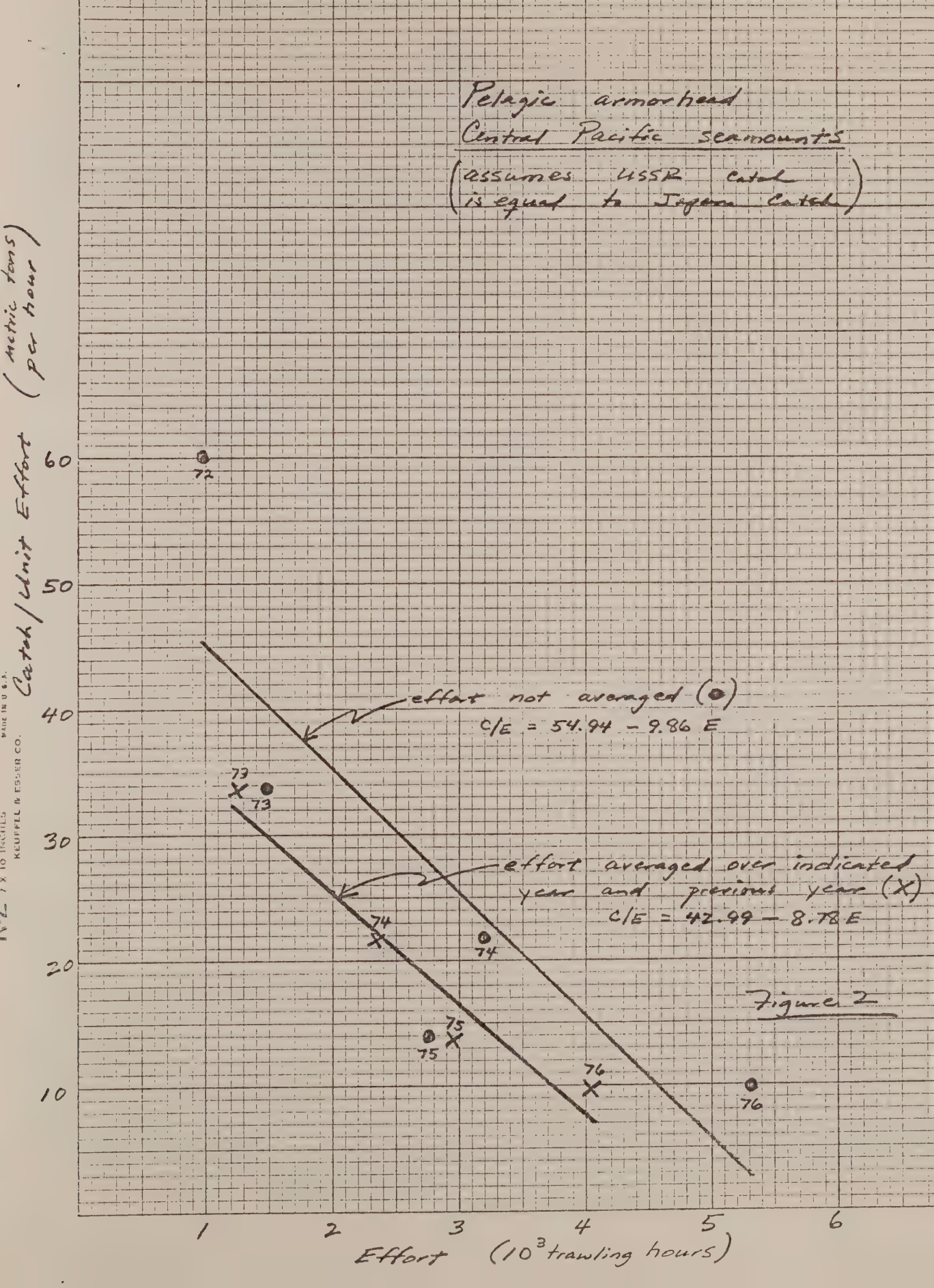
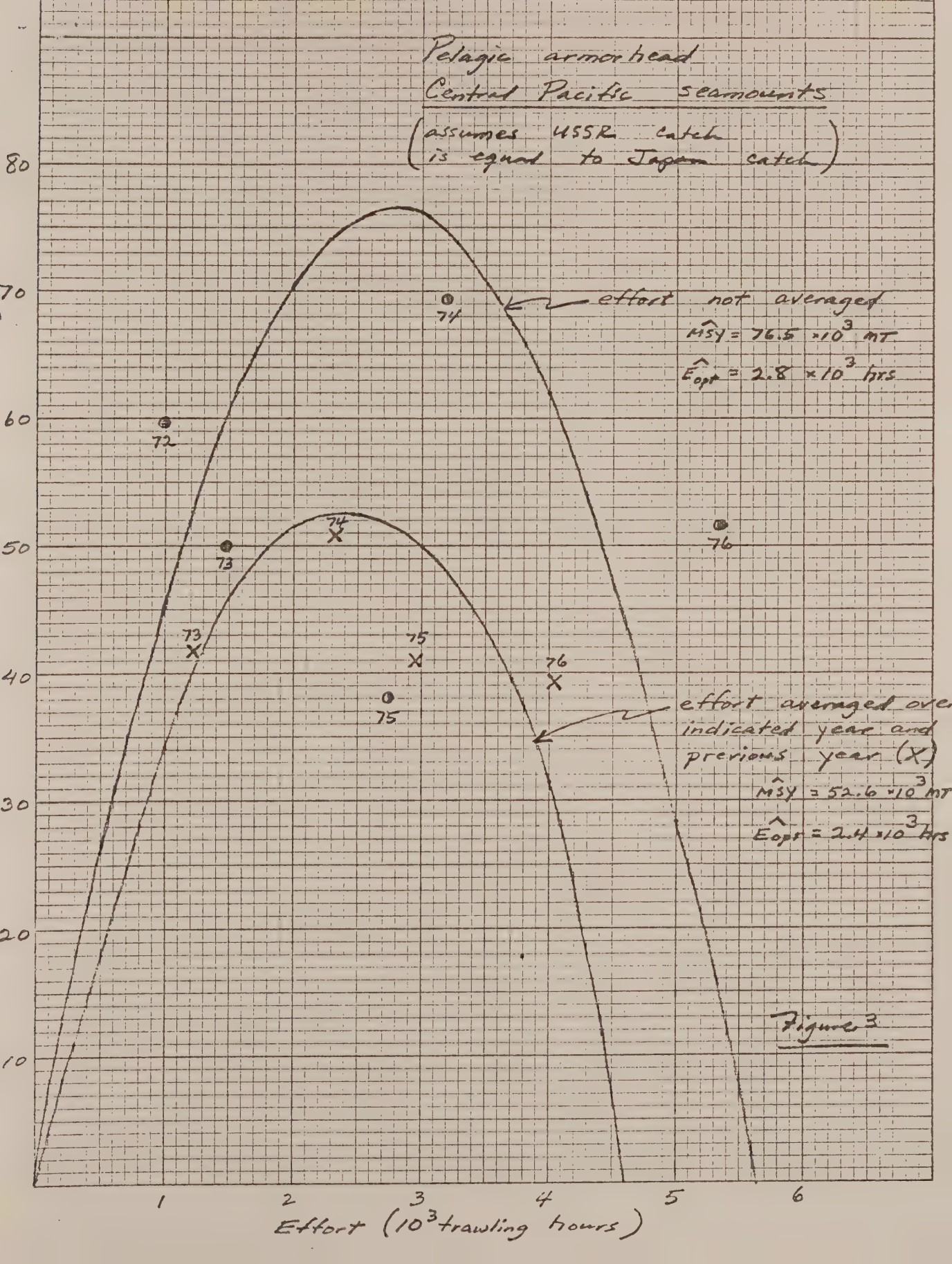

Pelagic armorhead
Central Pacific seamounts
(assumes USSR catch is equal to Japan Catch)
Catch / Unit Effort (metric tons per hour)
60
50
40
30
20
10
72
73
73
74
74
75
75
76
76
effort not averaged (●)
C/E = 54.94 − 9.86 E
effort averaged over indicated year and previous year (X)
C/E = 42.99 − 8.78 E
1
2
3
4
5
6
Effort (10³ trawling hours)

Figure 2


Pelagic armorhead
Central Pacific seamounts
(assumes 455R catch is equal to Japan catch)
effort not averaged
$\hat{MSY}$ = 76.5 ×10³ MT
$\hat{E}_{opt}$ = 2.8 ×10³ hrs
effort averaged over indicated year and previous year (X)
$\hat{MSY}$ = 52.6 ×10³ MT
$\hat{E}_{opt}$ = 2.4 ×10³ hrs
Figure 3
Effort (10³ trawling hours)
80
70
60
50
40
30
20
10
1
2
3
4
5
6
72
73
74
75
76
73
74
75
76

THE EFFECTS OF GRID SIZE AND APPROXIMATION TECHNIQUES ON THE SOLUTIONS OF MARKOV DECISION PROBLEMS

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DRAFT FOR COMMENT

ABSTRACT

Computational results are reported for the effect grid choice has on a solution to a Markov decision problem. The method used to discretize and reduce a continuous state problem can have significant effects on both the optimal policy calculated and on the estimated value of that policy. Tail probabilities of the ergodic distribution of an optimal policy appear to be quite sensitive to grid choice. Several a posterior measures of the error due to approximating the original problem on a reduced grid are compared with the actual error found.

I. In applying Markov decision processes (MDP's) to real life situations, an initial decision the modeler must face is the choice of grid over which to solve the problem. This arises because the problem is often described first as a stochastic model over a continuous state space; or else, the initial problem may be too large to solve.

The modeler must select an appropriate grid, "collapse" the original problem into the smaller problem by some method, solve the smaller problem, and extend both the optimal policy and the optimal value function back to the original problem. In this paper, several different techniques for choosing a grid are explored. Collapsing an MDP into a smaller grid is mathematically equivalent to aggregating or approximating MDP's as discussed in [8, 9, 10]. Section II explores how well different techniques perform for a model that arises in salmon management. For each technique, several different measures of performance are explored. Section III compares the results of section II with bounds that have been proposed for aggregated MDP's [3, 8, 9]. These bounds are checked both for how close they are to the true value of the performance measure, and also for how well they reflect the superiority of one particular method of aggregating and disaggregating over another. The reader is assumed to be familiar with both the notation and terminology in [3, 8, 9, 11].

II. Salmon spawn upriver in Alaska, and then the young salmon swim downriver to the ocean. Depending on the river, in a few years

the salmon return upriver to spawn again. The salmon are harvested by various types of fishermen as they run upriver. The released salmon are called spawners, the returning salmons recruits.

Mathews [2] has postulated the following spawner-recruit model for salmon in the Naknek River in Alaska: let x_t be the number of recruits that come upriver in period t, y_t the number of spawners released at the end of period t, and:

$$x_{t+1} = e^{d} 6.727\, y_t \exp\{-0.859\, y_t\}$$

where d is a random variable distributed as N(0, 0.1444). For computation the problem is discretized on the following grid (in units of 10^6 fish):

$$X = \{0,\ 0.125,\ 0.25,\ 0.375,\ 0.5,\ 0.625,\ 0.75,\ 0.875,\ 1,\ 1.175,$$
$$1.25,\ 1.375,\ 1.5,\ 1.625,\ 1.75,\ 1.875,\ 2,\ 2.5,\ 3,\ 3.5,\ 4,$$
$$4.5,\ 5,\ 5.5,\ 6,\ 6.5,\ 7,\ 7.5,\ 8,\ 8.5,\ 9\}$$

as follows:

State space = X

Decision space $Y(x) = \{y \mid 0 \leq y \leq x;\ y \in X,\ x \in X\}$

Transition probabilities: $\Pr\{x_{t+1} \leq \varepsilon \mid y_t\} = \Pr\{d \leq \ln(\varepsilon) - a \mid y_t\}$

where $a = \ln(6.727) + \ln(y_t) - 0.859\, y_t$

Given any $y \in X$, the probability of going to $x \in X$ is calculated as the difference of the cdf given y evaluated at x and the next smallest value in X.

This 31 point grid is considered for the purposes of this paper as the "original" problem. A discount factor of $\alpha = 0.97$ is used throughout, and the problem is to:

$$\text{maximize} \sum_{t=1}^{\infty} \alpha^{t-1}(x_t - y_t)$$

The optimal value function, optimal policy, ergodic distribution and gain rate for the original problem are given in Table 2.1. It is known a priori (see [4]) that a base stock policy is optimal. The true optimal policy has a base stock size of 750,000 fish, a mean annual harvest of 1,856,382 fish, and only a 3% chance of long run extinction, given the model.

The original grid was partitioned into 12 subsets as follows:

Subset No.	States in subset
1	0
2	0.125, 0.25, 0.375, 0.5
3	0.625, 0.75, 0.875, 1
4	1.125, 1.25, 1.375, 1.5
5	1.625, 1.75, 1.875, 2
6	2.5, 3
7	3.5, 4
8	4.5, 5
9	5.5, 6
10	6.5, 7
11	7.5, 8
12	8.5, 9

For the first trials, a reduced grid of

$$X_1 = \{0, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9\}$$

was selected. $Y(x)$ is defined as $\{y | 0 \leq y \leq x;\ y \in X_1,\ x \in X_1\}$ and the transition probabilities are calculated as:

$$\Pr\{x_{t+1} = x \in X_1 | y_t\} = \sum_{\substack{s \in \\ \text{subset} \\ \text{including } x}} \Pr\left\{x_{t+1} = s \in X | y_t\right\}$$

This follows [1, 9].

Two different one-period return functions were tried: the first uses the point estimate x-y. The second uses the average return from all states in a subset for which y is a feasible decision. For example, the return from choosing zero from state 0.5 is $5/16$. This second one-period return function was tried because it is the one-period return that results from aggregating the LP tableau for the MDP using fixed weight row and column aggregation (see Zipkin [11]) in order to arrive at the same reduced problem. For the second trials, a grid of

$$X_2 = \{0, 0.25, 0.75, 1.25, 1.75, 2.5, 3.5, 4.5, 5.5,$$
$$6.5, 7.5, 8.5\}$$

was used. This is the midpoint approximation to the partition. Transition probabilities and one-period returns are calculated as before.

Solutions to the aggregate problems were extended to the larger problem in a variety of ways. The optimal policy, since it is known to be of base stock form, was extended by the following rule: let x_i be the state used in the grid from the i^{th} partition, then:

$$y = \begin{cases} x, \text{ if } A(x_i) = x_i \\ \min\left(A(x_i), x\right) \text{ otherwise} \end{cases}$$

where $A(\cdot)$ is an optimal policy function.

Extensions of the optimal value function were calculated two ways. Method 1 involves a constant extension across a subset [1, 9], that is:

$$f(x) = f(x_i) \quad \text{for } x \in \text{subset } i$$

Method 2 consists of performing one iteration of successive approximations on the extended value function of method 1.

Five measures of comparison are used between the true solution and an approximate solution. Let $f(x)$ be the optimal value function of the original problem, and $e^{\sim}_{f(x)}$ the extension of the optimal value function for a reduced problem. Then measure one [9] is:

$$\sup_{x \in X} \left| f(x) - e^{\sim}_{f(x)} \right|$$

The second measure is $\left| \sum_x f(x) - \sum_x e^{\sim}_{f(x)} \right|$. $\sum_x f(x)$ is the value of the

Measures 3, 4, and 5 arise from the relationship between the dual variables of a linear programming solution to an MDP, and the discounted normalized fraction of years that we observed state x and take action y (Sobel [7]). If the sequence v_i, $i = 1, \ldots,$ number of states, is such that $v_i / \sum_i v_i$ equals the initial probability of being in state i, then:

$$\frac{(1-\alpha)\ \bar{u}_y^x}{\sum_i v_i} = \text{discounted normalized fraction of years that state x is observed and action y is taken.}$$

where $\bar{u}_y^x$ is an optimal dual variable in the LP. Measure 3 is:

$$\left| \frac{0.03}{31} \times \sum_x f(x) - \frac{0.03}{12} \times \sum_x \tilde{f}(x) \right| .$$

If the initial probability distribution is uniform, then

$$\frac{(1-\alpha)}{\text{Number of states}} \times \sum_{x \in X} f(x) = (1-\alpha) \sum_{x \in X} \sum_{y \in Y(x)} \bar{u}_y^x\, G(x, y)$$

which is the sum over all states and actions of the discounted fraction of years that (x, y) is observed times the return during those periods. In a sense, it is like a "discounted mean" harvest.

Measure 4 is the same as measure 3, except now the optimal policy from the smaller model is evaluated on the larger grid.

Measure 5 compares the cumulative discounted fraction of years that the Markov chain arising from an optimal policy is less than or equal to a given value on the different grids.

The results presented here are for the discounted fraction of years that a state-action pair are taken, starting from an initial uniform distribution. It should be mentioned, however, that similar qualitative results as what follows have also been found for the following cases:

(1) Discounted fraction of years starting from a non-uniform distribution

(2) Mean and tail behavior of the stationary distribution of the Markov chain that arises from following an optimal policy.

The particular results are chosen because they allow for consistent comparison of aggregation results from dynamic programming and from linear programming.

The eight trials are as follows:

Trial No.	State space	One-period return function	Method of extension
1	X_1	Point return	Constant over subset
2	X_1	Average return	Constant over subset
3	X_1	Point return	Successive approximation step
4	X_1	Average return	Successive approximation step
5	X_2	Point return	Constant over subset
6	X_2	Average return	Constant over subset
7	X_2	Point return	Successive approximation step
8	X_2	Average return	Successive approximation step

The results are summarized in Table 2.2 and in Figure 2.1. Average return from a given action over the partitions consistently performs better than the point return, for just about all grids and for most of the measures of comparison.

The midpoint of the partition as the selected state appears to give a better result than using endpoints. For this example it is necessary to be cautious in drawing conclusions, because the midpoint grid X_2 has the true base stock size in it, while the endpoint grid X_1 does not.

One iteration of successive approximation on the extended optimal value function produced only a small increase in accuracy in terms of measures 1 or 2. However, one iteration in all eight cases found the true optimal policy. Thus, though our estimate of the value function has not improved greatly, an optimal policy has been found. This one-step procedure is similar to that of [5], where the value of the equivalent deterministic model is calculated first. The computational equivalent of one iteration of successive approximation must be performed in calculating the bounds discussed in section III.

The one disturbing feature of this analysis is the comparisons of measure 5. In practice, in managing a fishery, both the probability of extinction and the probability of zero catch are of some concern, and often sensitivity analysis will be done describing the tradeoff between average per period catch and percentage of time there is no catch. Both grids X_1 and X_2, evaluated at their best policies (in the case of X_2 the true optimal policy) nearly triple discounted probability of extinction and the discounted fraction of years when there is no allowable catch as compared to the true value calculated on X (from 3.9% to 9.3%). Further, the estimated "discounted mean" harvest is off by amounts ranging from 12,000 fish to 1.6 million fish. This suggests that particularly when post-optimality analysis is being done, the grid should be expanded step by step until some stability is achieved in the key areas of interest.

One final trial was done. The absorbing state (zero) was dropped from the grid. The results are summarized in Table 2.3. The

value of the LP solution is 1,709.6359. The optimal policy is base stock with stock size 0.75. The "discounted mean" harvest is 1.6028. It is worth mentioning that when this problem is solved using successive approximations it took 320 iterations to converge at a tolerance of 0.0001. However, when methods of extrapolating forward to put bounds on the true value function are used [6], the same procedure converges in five iterations at the 0.0001 level. Computations with the absorbing state can be modified similarly in order to reduce the computational effort necessary.

III. In the previous section, a comparison is made of several ways of choosing a grid and aggregating a larger problem into a smaller problem. In that instance, the "true" original solution is known. However, usually grids and aggregation procedures are applied to problems where the "true" solution is never found. Several authors [3, 8, 9, 10] have developed bounds to compare the approximate solution with the unknown true solution. The reader is assumed to be familiar with the terminology and notation of these papers, and is referred to those articles for further details.

In this section, these bounds are calculated for several of the trial runs of the previous section. The different bounds are compared both as to how "tight" they are, and also as to how well they reflect the fact that one reduced problem gives a "better" solution than another. This certainly would be a desirable feature of any bound.

Whitt [9] derives both a priori and a posterior bounds of the form of measure 1:

$$\underset{\substack{x \in X \\ y \in Y(x)}}{\text{maximum}} \left| h\left(x, y, e_{\tilde{f}(x)}\right) - \tilde{h}\left(x, y, \tilde{f}(x)\right) \right|$$

where $$h\left(x, y, e_{\tilde{f}(x)}\right) = G(x, y) + \alpha \sum_j P^y_{xj} e_{\tilde{f}(j)}$$

and $\tilde{h}\left(x, y, \tilde{f}(x)\right)$ is similarly defined for the reduction of the full model into the smaller model. The a posterior bounds are calculated for trials 1, 2, 5, and 6, and the results are summarized in Table 3.1.

Table 3.1

Trial No.	A posterior bound	True value
1	379.5298	6.5643
2	347.57	2.3800
5	353.3910	6.4973
6	314.996	1.022

These bounds are very loose. For all of the trials, the bounds are much greater than the true optimal value function. The bounds do reflect, however, the superior performance of the grid X_2 and the average return function over the partition.

Bounds for measure 2 are given by [3, 8, 11]. These are summarized in Table 3.2. These bounds are calculated for the extended value function.

Table 3.2

Trial No.	Unimproved bound	Improved bound	Actual value of the absolute difference
1	$772.499 \leq z^* \leq 2{,}137.013$	$772.499 \leq z^* \leq 2{,}137.013$	164.2652
2	$689.79 \leq z^* \leq 2{,}978.533$	$689.79 \leq z^* \leq 2{,}314.5908$	60.4832
5	$646.1337 \leq z^* \leq 2{,}639.7954$	$646.1337 \leq z^* \leq 2{,}278.2525$	179.6471
6	$707.908 \leq z^* \leq 2{,}738.113$	$707.908 \leq z^* \leq 2{,}194.9325$	12.0681

The upper bounds for the partitions, p_k in the notation of [11], are given below.

Partition	Variables aggregated into choosing this action from each state in the partition										
	0	0.5 (0.25)	1 (0.35)	1.5 (1.25)	2 (1.75)	3 (2.5)	4 (3.5)	5 (4.5)	6 (5.5)	7 (6.5)	8 (7.5)	9 (8.5)
1	0	--	--	--	--	--	--	--	--	--	--	--
2	0	10	--	--	--	--	--	--	--	--	--	--
3	0	10	25	--	--	--	--	--	--	--	--	--
4	0	0	125	125	--	--	--	--	--	--	--	--
5	0	0	500	500	125	--	--	--	--	--	--	--
6	0	0	500	500	125	50	--	--	--	--	--	--
7	0	0	250	250	125	50	25	--	--	--	--	--
8	0	0	250	250	125	50	25	10	--	--	--	--
9	0	0	250	250	125	50	25	10	--	--	--	--
10	0	0	250	250	125	50	25	10	--	--	--	--
11	0	0	250	250	125	50	25	10	--	--	--	--
12	0	0	250	250	125	50	25	10	--	--	--	--

These bounds are reasonably tight, however they do not reflect which method of aggregation actually performs better. These bounds are tighter than the previous one for two reasons. Firstly, the bound in [9] essentially uses $\alpha/1-\alpha$ as the value for p_k, assuming there are 31 individual partitions. In this case, $\alpha/1-\alpha = 32.333$ which is 50% of any of the true values. The bounds in [8] calculated above allow for greater precision in the choice of p_k.

Secondly, the first bound includes any difference, whether positive or negative in sign. The second bound has a zero contribution to the error term from any column for which the extended vector is dual feasible in the LP solution to an MDP. This eliminates the entry that causes the larger absolute deviations in the first bound.

IV. Discussion

Several methods of approximating an MDP have been explored, and a posteriori bounds have been tested. The results seem to indicate:

1) When aggregating, it is best to use a state at a midpoint of the partition as the representative state from each subset of the grid.

2) The return function should be aggregated as the average return from each state in the partition for which the given action is feasible. Whenever feasible, one iteration of successive approximation should be done on the extended value function.

3) The actual error, by several criteria, is quite small. However, several key features of the long run probabilistic behavior of an optimal policy are sensitive to the grid size.

4) A posterior bounds can often be very loose, and may not reflect in fact how well one aggregate problem approximates the true problem as compared with a second aggregate problem.

5) The most important factor influencing the a posterior bounds is the value used to "blow up" the error terms by some appropriate amount. Little seems to be known of systematic or better ways to choose the values of these terms.

6) Convergence of successive approximations for the real models considered here is greatly speeded up by extrapolating an upper and lower bound for the true optimal value function, and using the largest of these differences as the convergence criterion. For one example, at a 0.0001 tolerance level, convergence was achieved in 5 iterations using this method as compared to 320 iterations required otherwise.

These results are not definitive, as they deal with one model over a very limited choice of grids. However, in most instances, the results can be explained in terms of the problem; this makes it reasonable to assume that these results are valid beyond this problem.

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Table 2.1.--Solution to the original problem.

State	Optimal value function	Discounted fraction of years that x_t is no greater than the given value
0	0	0.0323
0.125	59.7464	0.0333
0.25	60.3404	0.0342
0.375	60.7503	0.0353
0.5	61.0846	0.0364
0.625	61.3370	0.0376
0.75	61.5213	0.0391
0.875	61.6463	0.0416
1	61.7713	0.0460
1.125	61.8963	0.0536
1.25	62.0213	0.0660
1.375	62.1463	0.1078
1.5	62.2713	0.1389
1.625	62.3963	0.1760
1.75	62.5213	0.2183
1.875	62.6463	0.2645
2	62.7713	0.4620
2.5	63.2713	0.6398
3	63.7713	0.7718
3.5	64.2713	0.8594
4	64.7713	0.9140
4.5	65.2713	0.9472
5	65.7713	0.9668
5.5	66.2713	0.9786
6	66.7713	0.9858
6.5	67.2713	0.9903
7	67.7713	0.9933
7.5	68.2713	0.9954
8	68.7713	0.9971
8.5	69.2713	0.9991
9	69.7713	1.0
	1,918.167158	

Table 2.1.--Continued.

Optimal policy: Base stock given by y = minimum (x, 0.75)

"Discounted mean" harvest: 1.856382

Value of LP solution: 1,918.167158

Table 2.2a

Trial No.	Optimal policy	$\Sigma\tilde{f}(x)\left(\Sigma e_{\tilde{f}(x)}\right)$	Measures of "error" [1] Supremum norm on value function	[2] Deviation of LP solution	[3] Deviation of "discount mean" harvest	[4] Subopt. policy in full model
1	y = min(x, 1)	772.4990 (2,082.4323)	6.5643	164.2652	0.0750	0.0498
2	y = min(x, 1)	689.7904 (1,857.6839)	2.3800	60.4832	0.1318	0.498
3	y = min(x, 0.75)	(2,075.0572)	5.2263	156.8900	0.1518	0
4	y = min(x, 0.75)	(1,855.6727)	2.4056	62.4944	0.0605	0
5	y = min(x, 0.75)	646.1337 (1,738.5200)	6.4973	179.6471	1.6153	0
6	y = min(x, 0.75)	707.9084 (1,906.0990)	1.022	12.0681	0.0865	0
7	y = min(x, 0.75)	(1,742.8149)	6.1141	175.3523	0.1697	0
8	y = min(x, 0.75)	(1,905.8321)	0.4174	12.3351	0.0119	0

Table 2.2b

Discounted fraction of years that x_t is no greater than given value.

	Base stock size = 0.75 Midpoint of partition used	Base stock size = 1 Endpoint of partition used
x	Fraction of years	Fraction of years
0	0.0833	0.0833
0.25	0.0858	
0.5		0.0858
0.75	0.0934	
1		0.0909
1.25	0.1804	
1.5		0.1531
1.75	0.4852	
2		0.4187
2.5	0.7795	
3		0.7238
3.5	0.9151	
4		0.8858
4.5	0.9658	
5		0.9529
5.5	0.9844	
6		0.9792
6.5	0.9922	
7		0.9903
7.5	0.9965	
8		0.9957
8.5	1	
9		1

Table 2.3.--Optimal value function when zero is removed from the grid.

State	f(x)
0.125	53.1691
0.25	53.7283
0.375	54.0825
0.5	54.3591
0.625	54.5684
0.75	54.7241
0.875	54.8491
1	54.9741
1.125	55.0991
1.25	55.2241
1.375	55.3491
1.5	55.4741
1.625	55.5991
1.75	55.7241
1.875	55.8491
2	55.9941
2.5	56.0991
3	56.5991
3.5	57.0991
4	57.5991
4.5	58.0991
5	58.5991
5.5	59.0991
6	59.5991
6.5	60.0991
7	60.5991
7.5	61.0991
8	61.5991
8.5	62.0991
9	62.5991
Value of LP solution =	1,709.6359
Opt policy =	y = min (x, 0.75)

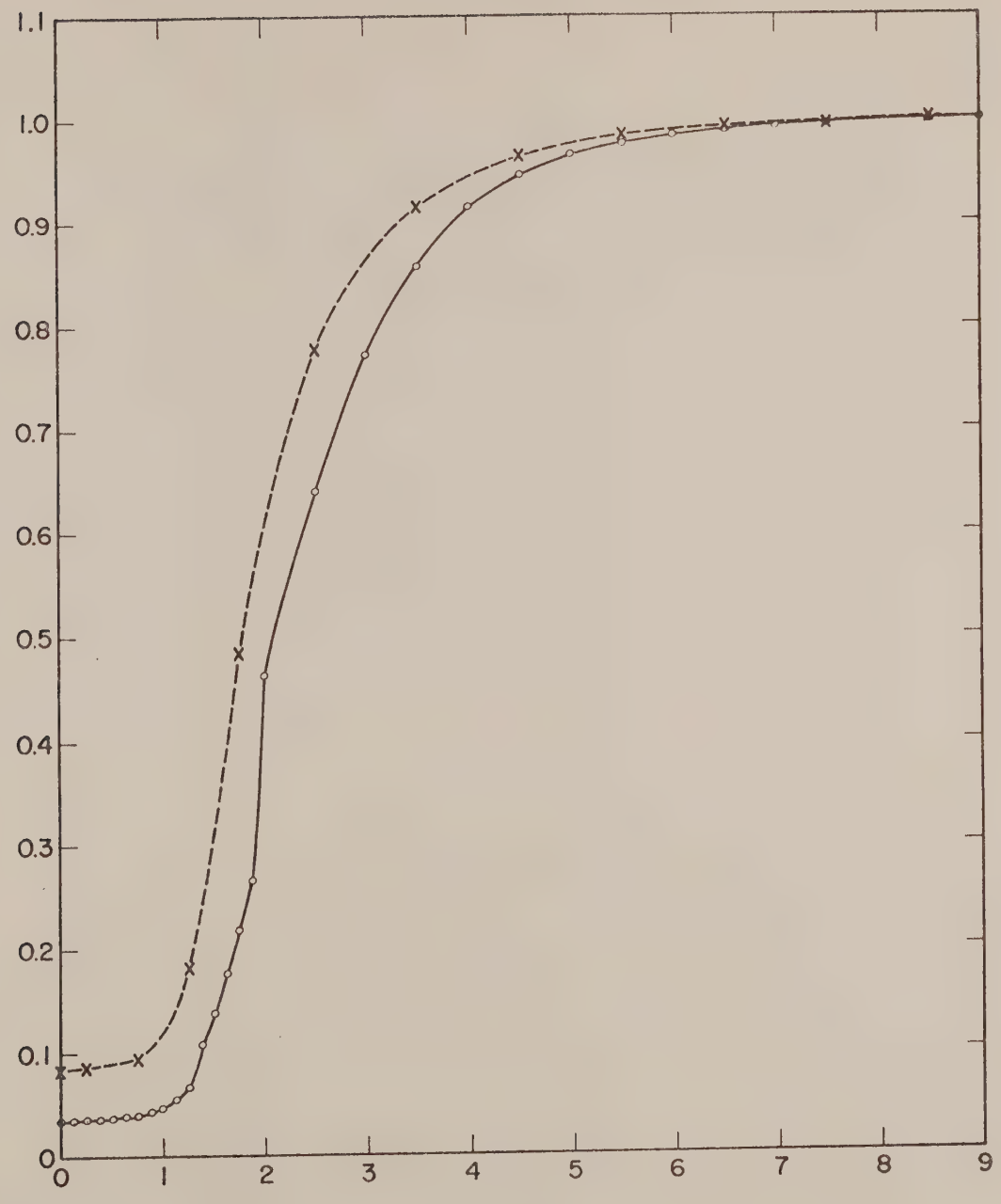

Figure 2.1.--Graph of distributions from Table 2.2b.

USE OF AGE-SPECIFIC ABUNDANCE INDICES AND EFFECTIVE EFFORT STATISTICS TO ASSESS THE NORTH PACIFIC ALBACORE STOCK - PRELIMINARY RESULTS

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This is a draft working paper prepared for discussions at the Third North Pacific Albacore Workshop. It is not intended for publication in its present form and should not be cited without permission from its authors.

INTRODUCTION

This paper is concerned with the use of age-specific indices of abundance and effective effort statistics for estimating vital parameters of fish population dynamics and for predicting stock size and catch. It is motivated by the apparent need in tuna management analysis for a more formal way of combining information on relative stock size and age composition. Most tuna stock assessment is based on production model analyses of catch and catch-per-unit effort (CPUE) statistics. In this approach, a basic assumption is that age structure is not important. Further, the emphasis is usually on static properties of the underlying model, such as maximum sustainable yield (MSY), and little attention is paid to annual forecasts of stock size or catch.

However, in many cases age-composition estimates are available along with the catch and catch-per-effort data. These are commonly used in cohort analyses and to compute indices of reproductive potential (e.g., population fecundity) or indices of recruitment. The side information on reproductive potential and recruitment strength can be used to modify appraisals of stock condition based solely on a production model analysis and the results of cohort analysis may lead to a yield per recruit assessment and to conservation measures based on optimum harvest size. Still, it seems there is no technique now in use which fully integrates the available fishery statistics and produces both steady state information for determining general harvest strategy and short-term predictions of stock size and catch for use in tactical planning.

The approach we describe is a simple synthesis of existing theory and technique. In operation it involves the following steps at the end of each year:

(1) Compute age-specific indices of abundance, using CPUE statistics and size-composition data, and the best available growth model.

(2) Using the abundance indices and total age-specific catch data, estimate age-specific effective fishing effort.

(3) Revise estimates of mortality coefficients and coefficients of catchability using updated statistics on age-specific abundance and effective effort.

(4) Estimate spawning biomass using the latest indices of abundance and catchability coefficient estimates.

(5) Recompute estimates of parameters for spawner-recruit model, using updated estimates of recruitment and spawning biomass.

(6) Forecast recruitment for next year, using revised parameter values and estimates of spawning biomass for appropriate parent stock.

(7) Forecast abundance of other age groups using past year's age-specific abundance indices and revised estimates of mortality rates.

(8) Predict the coming year's catch using the forecasted stock size and expected fishing effort.

In the following sections we briefly outline the method and describe a trial application to North Pacific albacore, Thunnus alalunga. Basic equations are presented; for the most part these are conventional and fully described in the literature (e.g., Ricker 1975). In applying the technique to the albacore fishery we used catch, CPUE, and size-composition data from the major Japanese and United States fisheries over the 1955-75 period. Some fairly strong assumptions were made and several short-cuts were taken. Serious statistical problems were encountered in step (3) above, which terminated our work at this stage. These are briefly diagnosed, and comments are made concerning our intended continuation of the study.

NOTATION

Let

$N_{k,i}$ = number of fish in age group k at beginning of i^{th} year

$P_{k,i}$ = number of fish in age group k at beginning of index period for that age group in year i

$\bar{P}_{k,i}$ = average abundance of fish of age group k during their index period in year i

$U_{k,i}$ = average CPUE for fish in age group k during their index period in year i

$S_{k,i}$ = survival rate for fish in age group k during year i

$\bar{w}_k$ = average weight of individual fish of age group k during their index period

$\bar{W}_{k,i}$ = average biomass of fish in age group k during their index period in year i

$\simeq \bar{w}_k \bar{P}_{k,i}$

B_i = spawning biomass during year i

M_k = instantaneous natural mortality coefficient (annual) for fish in age-group k

λ_k = catchability availability coefficient for fish in age group k

= ratio of instantaneous fishing mortality coefficient (annual) to effective effort statistic

$= F_{k,i} / E_{k,i}$

$E_{k,i}$ = total effective effort exerted on fish in age group k in year i

$C_{k,i}$ = total number of fish of age group k caught in year i

$\varepsilon_{k,i}$ = effort exerted on fish in age group k during their index period in year i

$X_{k,i}$ = effort exerted on fish in age group k from the beginning of year i to the beginning of the index period for age group k

Δ_k = length of index period for age group k

τ_k = time at beginning of index period for age group k, relative to beginning of year

BASIC RELATIONS

We assume the exploitable population at the beginning of year i is composed of survivors from the previous year's exploitable stock and newly recruited fish. We assume the number of recruits in year i, entering the population on January 1 is

$$N_{r,i} = \alpha B_{i-\delta} e^{-\beta B_{i-\delta}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where δ is the recruitment lag and $B_{i-\delta}$ is the spawning biomass in the parent year. For fish in the other age groups ($k > r$) we assume the initial abundance in year i is related to the initial abundance in year i-1 by

$$N_{k,i} = N_{k-1,i-1} e^{-(M_{k-1} + \lambda_{k-1} E_{k-1,i-1})} \quad \ldots \quad (2)$$

Thus the rate of survival for fish in age group k-1 in year i-1 is defined as

$$S_{k-1,\ i-1} = \frac{N_{k,\ i}}{N_{k-1,\ i-1}} = e^{-(M_{k-1} + \lambda_{k-1} E_{k-1,\ i-1})} \quad . \quad . \quad (3)$$

At the beginning of the index period for age group k, the abundance of that group is

$$P_{k,\ i} = N_{k,\ i} e^{-(M_k \tau_k + \lambda_k X_{k,\ i})} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

We assume the average CPUE on fish of age group k during their index period is proportional to their average abundance during the period, i.e.,

$$U_{k,\ i} = \lambda_k \bar{P}_{k,\ i} \simeq \lambda_k P_{k,\ i} e^{-(M_k \Delta_k + \lambda_k \varepsilon_{k,\ i})/2} \quad . \quad . \quad . \quad . \quad (5)$$

To complete the set of basic equations, let $D_{k,\ i}$ be the average abundance of fish in age group k during a defined spawning period of year i.

Then

$$B_i = \sum_k v_k \bar{w}_k D_{k,\ i} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where v_k is a coefficient of reproductive potential per unit biomass and $\bar{w}_k$ is average weight of an individual fish in age group k during the spawning period.

$D_{k,\ i}$ can be defined in the same fashion as $\bar{P}_{k,\ i}$ was above,

i.e. $D_{k,\ i} = f\left\{\frac{U_{k,\ i}}{\lambda_k}\right\} = f\left\{\bar{P}_{k,\ i}\right\}$.

COMPUTING EFFECTIVE EFFORT

Total effective effort on age group k in year i is computed as

$$E_{k,\,i} = \frac{C_{k,\,i}}{U_{k,\,i}} \quad . \qquad \ldots\ldots\ldots\ldots \quad (7)$$

Effective efforts for subintervals of the year, such as $X_{k,\,i}$ and $\varepsilon_{k,\,i}$, are computed analagously using subsets of the age-specific catch data.

Note that $U_{k,\,i} = \lambda_k \bar{N}_{k,\,i}$

where $\bar{N}_{k,\,i}$ is the average abundance of age group k during the year. Also, $C_{k,\,i} = \lambda_k E_{k,\,i} \bar{N}_{k,\,i} = F_{k,\,i} \bar{N}_{k,\,i}$

where $F_{k,\,i}$ is the average fishing mortality coefficient for age group k during year i.

FORECASTING ABUNDANCE AND CATCH

Given the estimate of spawning biomass for year $i-\delta$ and estimates of the parameters α and β, the abundance of recruits at the beginning of year i, $N_{r,\,i}$, may be predicted using equation (1).

The initial abundance of fish in other age groups may be estimated using the relation

$$\hat{N}_{k,\,i} = \left(\frac{U_{k-1,\,i-1}}{\lambda_{k-1}}\right) e^{-M_{k-1}(1-\tau_{k-1} - \Delta_{k-1}/2)} \times e^{-\lambda_{k-1}(E_{k-1,\,i-1} - X_{k-1,\,i-1} - \varepsilon_{k-1,\,i-1}/2)} \quad . \; . \; . \quad (8)$$

The required inputs for this predictor are the age-specific indices of abundance for the previous year, the age-specific effective effort statistics for the previous year, and estimates of the coefficients M and λ. These two coefficients are age-specific.

Once the initial population abundance is predicted, the age-specific catch for year i may be forecasted, given an estimate of expected fishing effort, i.e.,

$$\hat{C}_{k,\,i} = \left(\frac{g\,E_{k-1,\,i-1}}{M_k + g\,E_{k-1,\,i-1}}\right)\left(1 - e^{-(M_k + g\,E_{k-1,\,i-1})}\right)\hat{N}_{k,\,i} \quad . . .(9)$$

where g is the multiplier relating last season's effort to the expected effort in season i.

ESTIMATING M AND λ

By substituting (5) in (4) an estimator for $N_{k,\,i}$ is found, leading to

$$\hat{S}_{k-1,\,i-1} = \frac{\hat{N}_{k,\,i}}{\hat{N}_{k-1,\,i-1}} \quad .$$

This is manipulated to yield the well-known result

$$-\ln\left(\frac{U_{k,\,i}}{U_{k-1,\,i-1}}\right) \simeq \ln\left(\frac{\lambda_{k-1}}{\lambda_k}\right) + M_{k-1}(1 - \tau_{k-1} - \Delta_{k-1}/2)$$

$$+ M_k(\tau_k + \Delta_k/2)$$

$$+ \lambda_{k-1}(E_{k-1,\,i-1} - X_{k-1,\,i-1} - \varepsilon_{k-1,\,i-1}/2)$$

$$+ \lambda_k(X_{k,\,i} + \varepsilon_{k,\,i}/2)$$

An estimation scheme may be developed around this equation, using ordinary multiple linear regression analysis. Since the time intervals are assumed to be the same each year, the two natural mortality terms are not separately estimable without further assumptions. The assumption we made was that $M_{k-1} = M_k = M$ for all k, i.e., that the natural mortality rate was constant.

ESTIMATING α AND β

Once the above parameters have been estimated, spawning biomass can be computed for each year. Also the recruitments may be back-estimated using

$$\hat{N}_{r,\,i} = \frac{U_{r,\,i}}{\lambda_r}\, e^{M_r(\tau_r + \Delta_r/2) + \lambda_r(X_{r,\,i} + \varepsilon_{r,\,i}/2)}$$

Once this is done, parameters of the Ricker spawner-recruit model may be estimated in the usual way with a linear regression based on the equation

$$\ln \frac{\hat{N}_{r,\,i}}{\hat{B}_{i-\delta}} = \ln\alpha - \beta \hat{B}_{i-\delta}\,.$$

DATA SOURCES

Indices of abundance were constructed using information on (1) total catch, CPUE, and size composition for the Japanese pole-and-line fishery, (2) catch, effort, and size composition for the Japanese longline fishery, and (3) catch and size composition for the U.S. west coast albacore fisheries.

The completeness and source of the data are described in Table 1. Some of the relevant statistics were available for 1976 and 1977, but not the complete set, so indices were computed only from 1955, when the pole-and-line CPUE data begin, to 1975.

INDICES OF ABUNDANCE AND INDEX AREAS

We considered two possible indices of stock abundance. (1) The number of albacore caught per vessel-day in the Japanese pole-and-line fishery, and (2) the number of albacore caught per 1,000 hooks in the Japanese tuna longline fishery. Indices were not developed using United States troll fishery data because the data series is relatively short and the availability of albacore varies markedly in time and space.

In the case of pole-and-line indices, catch rate data for 1955-69 were from vessels landing at Yaizu. This sample information was assumed to be representative of the entire pole-and-line fleet. For the 1970-75 period the pole-and-line data were taken from issues

of the "Annual report of effort and catch statistics by area, Japanese skipjack baitboat fishery" published by the Fisheries Agency of Japan. The pole-and-line catch rate data were combined with length-composition statistics and with size-age relationships given by Clemens (1961), and the age-specific catch in numbers of fish was computed in such a way that the associated total weight yields equaled the figures reported at the 1977 North Pacific Albacore Workshop. [Clemens' value for the von Bertalanffy parameter t_o was increased by one year.]

Possible index areas for the Japanese pole-and-line fishery were selected as shown in Figure 1. Each area is a block of 5° lat. by 10° long. Areas PL-2 and PL-3 correspond to the Nishinoshima Area described by Shiohama (1975), areas PL-5 and PL-6 coincide with Shiohama's Izu Area, and areas PL-6 through PL-12 are in the Kuroshio Front region.

In the case of the Japanese longline fishery, nine index areas were established, areas LL-1 through LL-9, each being a band of 5° lat. These areas cover the entire North Pacific albacore longline grounds (Figure 2). In addition to the smaller index areas, we defined aggregate index areas, PL-T and LL-T. Area PL-T is composed of the pole-and-line areas PL-2, PL-3, PL-5, and PL-6. Area LL-T consists of the longline index areas LL-3 through LL-7.

ESTIMATES OF TOTAL CATCH AND EFFECTIVE EFFORT

In each index area the following computations were made: (1) First the available catch rate data were combined with the size-

composition statistics to produce the average catch rates by 1-cm length interval, by quarter, for each index area.

(2) The catch rates by length class interval were converted to quarterly age-specific catch rates, by directly applying the modified Clemens growth model.

(3) Steps (1) and (2) were followed with total catch statistics in place of CPUE data, and, the quarterly catches of albacore [number of fish] by age group were computed, aggregated over the Japanese and United States fisheries.

(4) The first quarter of the year was chosen as the standard index period for the longline fishery, and the second quarter was selected for the pole-and-line fishery.

(5) In each proposed index area, the age-specific abundance indices (catch rates) during the selected indexing period were divided into the age-specific total catch estimates to produce a set of quarterly total effective effort statistics.

Figure 3 shows 21-year sequences of abundance indices, all age groups combined. Both pole-and-line and longline indices show a reduction in apparent abundance since the mid-1960's, when catch rates were relatively high. The age-specific indices of abundance are given in Tables 2 and 3. The pole-and-line indices represent area PL-T in the second quarter of the year, and the longline indices are from LL-T in the first quarter. Total age-specific catch estimates are given in Table 4. Table 5 gives the aggregate annual statistics on catch as well as the abundance indices and effective effort statistics based on both the pole-and-line and longline fisheries.

RESULTS OF REGRESSION ANALYSES

Regression analyses based on equation (10) were carried out using abundance indices and total effective effort statistics from PL-9 for age classes 2 and 3, data from PL-6 for age groups 4 and 5, and data from area LL-19 for ages 6-11. The regression analysis was also applied to the age-specific indices in area PL-T and LL-T. In most cases a complete set of 20 data points was available for the analysis; if either $U_{k,\,i}$ of $U_{k-1,\,i-1}$ was zero the particular data point was omitted.

If the data actually represent what we assumed they do in constructing the model, then the two regression coefficients (besides the constant terms) should be positive. However, these expectations were met in only 2 out of the 31 regressions we carried out. In five cases estimates of λ_k and λ_{k-1} were both negative. In the remaining 24 analyses the estimate of λ_k had a positive sign but the estimate of λ_{k-1} was negative.

These unfortunate results can be traced, at least in part, to the negative correlation between $U_{k,\,i}$ and $E_{k,\,i}$. The correlation between the two variables arises because $E_{k,\,i}$ is computed as in equation (7), by dividing the age-specific catch by $U_{k,\,i}$. The same difficulty is encountered in production model analyses when the effective effort is computed in this manner, or simply when the index of abundance is derived by dividing catch by effort and then regressed against the effort statistic.

COMMENTS ON FUTURE WORK

Our work on the age-specific abundance indices and the forecasting scheme is now halted until we solve the problem of estimating effective effort. In addition to this problem, there are other concerns needing attention:

(1) The abundance indices themselves may be questioned because of the way age composition was computed. Instead of the use of the age-length key, a short-cut procedure, we will calculate the age-specific catch by analyzing the modes of the distribution of catch by length-class interval.

(2) Because of the way total effective effort was computed, a tacit assumption in the model described here is that the average age-specific abundance during the specified index period is identical to the annual average abundance, i.e., $\bar{P}_{k,\,i} = \bar{N}_{k,\,i.}$ In searching for a different effective effort measures, we hope to be able to eliminate this assumption.

(3) In outlining our forecasting scheme we neglected the effects of environmental conditions, either on stock size or expected catch.

(4) Our preliminary analysis did not consider the possibility that there is more than one stock of North Pacific albacore.

(5) In developing the pole-and-line abundance indices, we did not take into account changes in the average size of vessels in the fleet or the variation in relative fishing power of vessels

operating on different fishing grounds. Other CPUE statistics, such as catch per pole-day, may be preferable.

These are some of the considerations we will bear in mind in future exploratory work. Our objective remains to develop comprehensive and effective procedures for estimating stock condition and forecasting catch.

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Table 1.--Kinds of North Pacific albacore data used in the analysis, their completeness, and source.

Fishery	Type of data	Temporal and spatial completeness	Source
Japanese pole-and-line	Total landings	By year, 1955-75 All areas combined	Far Seas Fisheries Research Laboratory, Shimizu, Japan (FSFRL)
	Yaizu sample catch and nominal effort	By year, 1955-69 By month, Mar.-Sept. By 5° lat., 10° long. areas (25°-35°N, 130°-180°E; and 35°-45°N, 140°-180°E)	FSFRL
	Catch and nominal effort	By year, 1970-75 By month By 1° lat., 1° long. areas	"Annual Report of Effort and Catch Statistics by Areas, Japanese Skipjack Baitboat Fishery," Fisheries Agency of Japan
	Sample length composition	By year, 1955-64 By month, May-July By 10° long. bands (north of 25°N, 130°-160°E)	1955-59 in Suda (1963) 1960-64 in Koto and Hisada (1966)
		By year, 1965-71 By month, Jan.-Dec. By 5° lat., 10° long. areas (east of 120°E)	Shiohama (1973)
		1972-75 By month, Mar.-Oct. By 5° lat., 10° long. areas (east of 130°E)	FSFRL
Japanese longline	Total catch and nominal effort	By year, 1955-75 By month, Jan.-Dec. By 5° lat., 5° long. areas (east of 120°E)	"Annual Report of Effort and Catch Statistics by Area on Japanese Tuna Longline Fishery," Fisheries Agency of Japan
	Sample length composition	By year, 1955-64 By month, Dec.-Feb. By 10° long. bands (north of 25°N, 130°-180°E)	1955-59 in Suda (1963) 1960-64 in Koto and Hisada (1966)
		By year, 1965-75 By month, Jan.-Dec. By 5° lat., 10° long. areas (east of 120°E)	1965-71 in Shiohama (1973) 1972-75 from FSFRL
United States	Total landings (troll and baitboats)	By year 1955-75 By month, by state (California, Oregon and Washington)	California Department of Fish and Game, Long Beach, California (CFG) and NMFS, La Jolla, California
	Length composition (troll only)	By year, 1955-72 for California and Oregon (except 1964 for Oregon); By year, 1955-68 for Washington (several years of Washington size compositions estimated from Oregon data)	CFG Also, California data for 1955-61 published in Clemens and Craig (1965); Oregon data for 1955-60 published in Ayers and Meehan (1963); Oregon data for 1961-67 published in Meehan and Hreha (1969); Oregon data for 1968-72 published in Hreha (1974).
		1973-75 States combined	NMFS, La Jolla, California

Table 2.--Estimated age-specific abundance indices for albacore in area PL-T during second quarter (fish per vessel-day).

Year	Age group (years) 2	3	4	5	6	7	8
1955	--	1.17	329.74	75.87	9.88	0.21	--
1956	1.16	89.75	230.83	22.62	15.16	0.43	--
1957	6.12	58.61	124.55	91.39	14.90	0.07	--
1958	1.56	70.61	220.91	126.80	23.80	0.54	--
1959	0.02	0.63	81.45	101.25	31.76	1.54	--
1960	0.05	2.77	170.49	30.38	6.32	0.10	--
1961	7.42	--	80.15	187.58	38.76	1.86	--
1962	3.71	--	43.95	171.93	259.50	8.51	0.31
1963	--	3.17	317.00	51.98	10.13	0.19	--
1964	24.02	30.67	32.67	238.09	48.86	0.09	--
1965	275.88	88.23	60.53	329.67	78.78	5.68	--
1966	47.54	33.05	39.12	284.63	104.27	4.04	0.20
1967	5.02	27.45	22.66	237.46	86.79	15.66	1.02
1968	18.95	15.48	50.17	140.79	67.60	38.00	1.31
1968	3.47	1.69	30.86	248.41	27.32	2.18	0.74
1970	7.00	10.02	14.26	79.66	20.52	1.33	0.10
1971	2.65	7.62	39.39	127.12	53.00	11.65	0.07
1972	8.80	26.50	75.66	91.04	7.37	3.25	0.51
1973	7.49	4.72	17.10	165.61	61.38	7.72	1.77
1974	8.78	14.68	75.11	71.44	20.15	12.18	8.46
1975	12.62	37.11	57.21	83.71	20.60	3.66	0.17

Table 3.--Estimated age-specific abundance indices for albacore in area LL-T during the first quarter (fish per 1,000 hooks).

Year	Age group (years) 2	3	4	5	6	7	8	9	10	11
1955	0.01	0.55	0.59	2.39	1.24	0.53	0.35	0.20	0.08	0.02
1956	0.04	0.32	1.81	2.13	0.51	0.37	0.16	0.07	0.03	0.02
1957	0.04	0.64	3.27	2.88	1.47	0.92	0.34	0.11	0.07	0.03
1958	0.02	0.54	2.49	2.29	1.87	1.05	0.50	0.11	0.05	0.02
1959	--	0.23	0.76	3.48	1.81	1.00	0.72	0.31	0.09	0.02
1960	--	0.07	0.76	2.86	1.05	0.62	0.38	0.15	0.05	0.03
1961	0.01	0.12	0.49	3.83	1.14	0.81	0.35	0.10	0.04	0.01
1962	0.05	1.20	1.06	0.80	0.89	1.56	0.71	0.24	0.11	0.03
1963	0.01	0.49	1.00	1.34	0.28	0.28	0.35	0.07	0.02	--
1964	--	0.20	1.80	2.79	0.94	0.36	0.28	0.21	0.12	0.04
1965	--	0.57	1.50	1.78	0.48	0.28	0.31	0.30	0.19	0.09
1966	0.59	0.86	3.83	2.98	0.97	0.86	0.76	0.41	0.26	0.17
1967	0.35	0.86	3.45	1.91	1.77	1.28	1.07	0.59	0.31	0.13
1968	0.08	2.07	2.26	1.35	1.53	1.22	0.95	0.39	0.13	0.05
1969	--	0.14	3.08	1.21	0.73	0.85	1.07	0.66	0.18	0.02
1970	0.11	1.93	2.10	1.14	0.84	0.44	0.47	0.34	0.23	0.12
1971	0.10	0.24	0.72	1.56	0.70	0.92	0.83	0.54	0.37	0.09
1972	--	0.12	2.71	0.90	0.75	1.31	1.16	0.40	0.20	0.14
1973	--	0.01	0.84	0.78	0.90	0.94	1.06	0.58	0.25	0.13
1974	0.01	0.34	0.56	0.84	1.27	1.00	0.63	0.31	0.14	0.13
1975	--	0.03	0.38	0.54	0.41	0.66	0.71	0.42	0.32	0.18

Table 4.--Estimates of total age-specific albacore catch (10^3 fish)

Year	Age group (years) 2	3	4	5	6	7	8	9	10	11
1955	238	2,320	256	565	279	132	245	479	60	33
1956	153	3,200	4,101	684	328	100	38	15	8	4
1957	192	2,422	3,244	2,055	469	139	60	17	9	4
1958	174	1,878	1,746	1,121	390	149	74	18	7	3
1959	223	2,915	709	1,035	379	144	98	41	12	4
1960	13	1,610	2,701	1,063	286	122	67	29	9	4
1961	142	590	1,509	1,530	313	177	76	21	7	3
1962	402	2,926	630	437	430	204	96	34	14	4
1963	256	3,221	3,080	758	170	85	80	24	10	1
1964	412	2,141	2,102	1,295	292	50	37	28	16	6
1965	131	1,436	1,797	2,501	425	61	38	25	13	7
1966	205	1,642	1,560	1,652	514	118	85	39	22	16
1967	272	2,465	1,393	2,100	770	266	140	61	29	15
1968	202	3,027	1,480	754	529	268	141	45	16	7
1969	129	2,227	1,359	2,218	328	162	162	76	22	5
1970	614	2,561	1,849	1,079	435	109	77	46	30	13
1971	237	3,499	1,866	2,183	611	151	108	50	25	9
1972	4,072	2,539	3,128	2,442	343	234	245	99	58	29
1973	8,556	2,039	958	2,569	891	293	183	97	50	29
1974	1,435	3,832	4,985	1,382	420	260	165	83	40	35
1975	386	3,464	1,943	1,648	603	141	113	66	43	26

Table 5.--Aggregate statistics on albacore catch, catch-per-effort, and effective effort.

Year	C 10^3 fish	Pole-line U Fish/vessel-day	Longline U Fish/10^3 hooks	Pole-line E 10^3 vessel-days	Longline E 10^6 hooks
1955	4,606	417	5.97	11.0	772
1956	8,630	360	5.46	24.0	1,580
1957	8,611	296	9.75	29.1	883
1958	5,559	444	8.95	12.5	621
1959	5,560	217	8.41	25.7	661
1960	5,904	210	5.96	28.1	991
1961	4,367	316	6.89	13.8	634
1962	5,177	488	6.66	10.6	778
1963	7,684	382	3.83	20.1	2,008
1964	6,378	374	6.73	17.0	948
1965	6,435	839	5.51	7.7	1,168
1966	5,852	513	11.70	11.4	500
1967	7,512	396	11.73	19.0	641
1968	6,470	332	10.02	19.5	646
1969	6,687	315	7.96	21.3	840
1970	6,812	133	7.72	51.3	883
1971	8,738	241	6.07	36.0	1,439
1972	13,188	213	7.70	61.9	1,712
1973	15,664	266	5.50	58.9	2,848
1974	12,636	211	5.24	59.9	2,411
1975	8,432	215	3.65	39.2	2,309

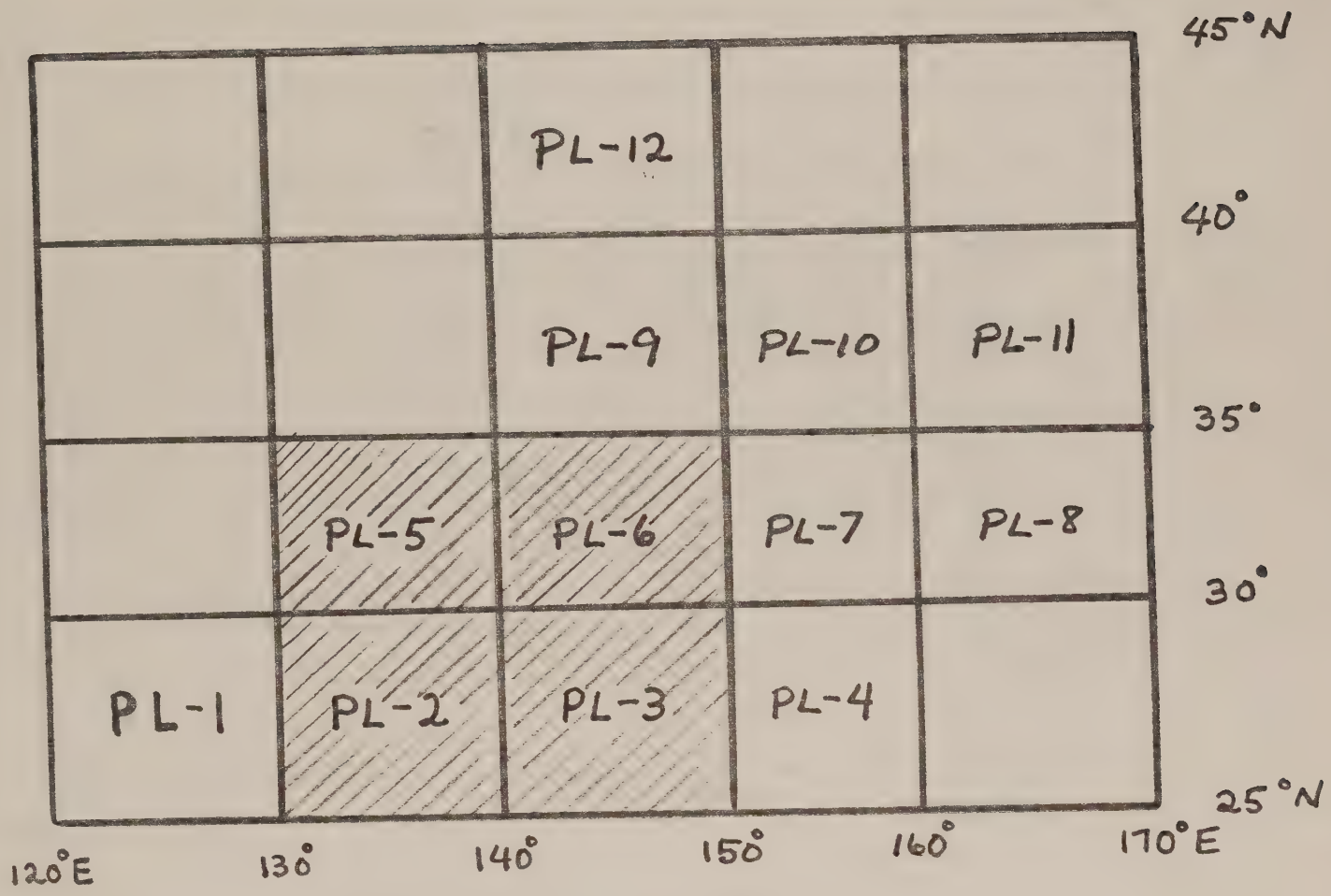


Figure 1.--Pole-and-line index areas.

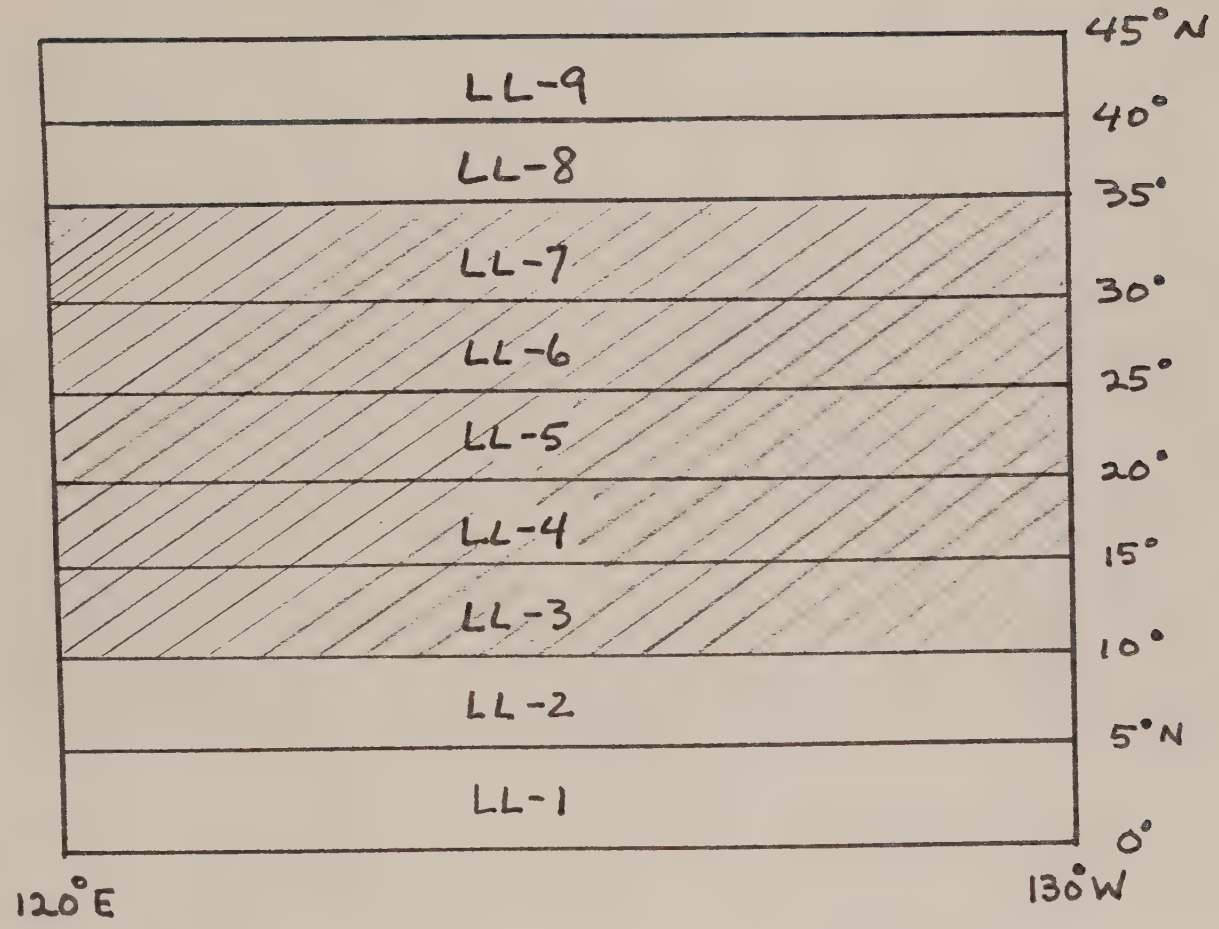
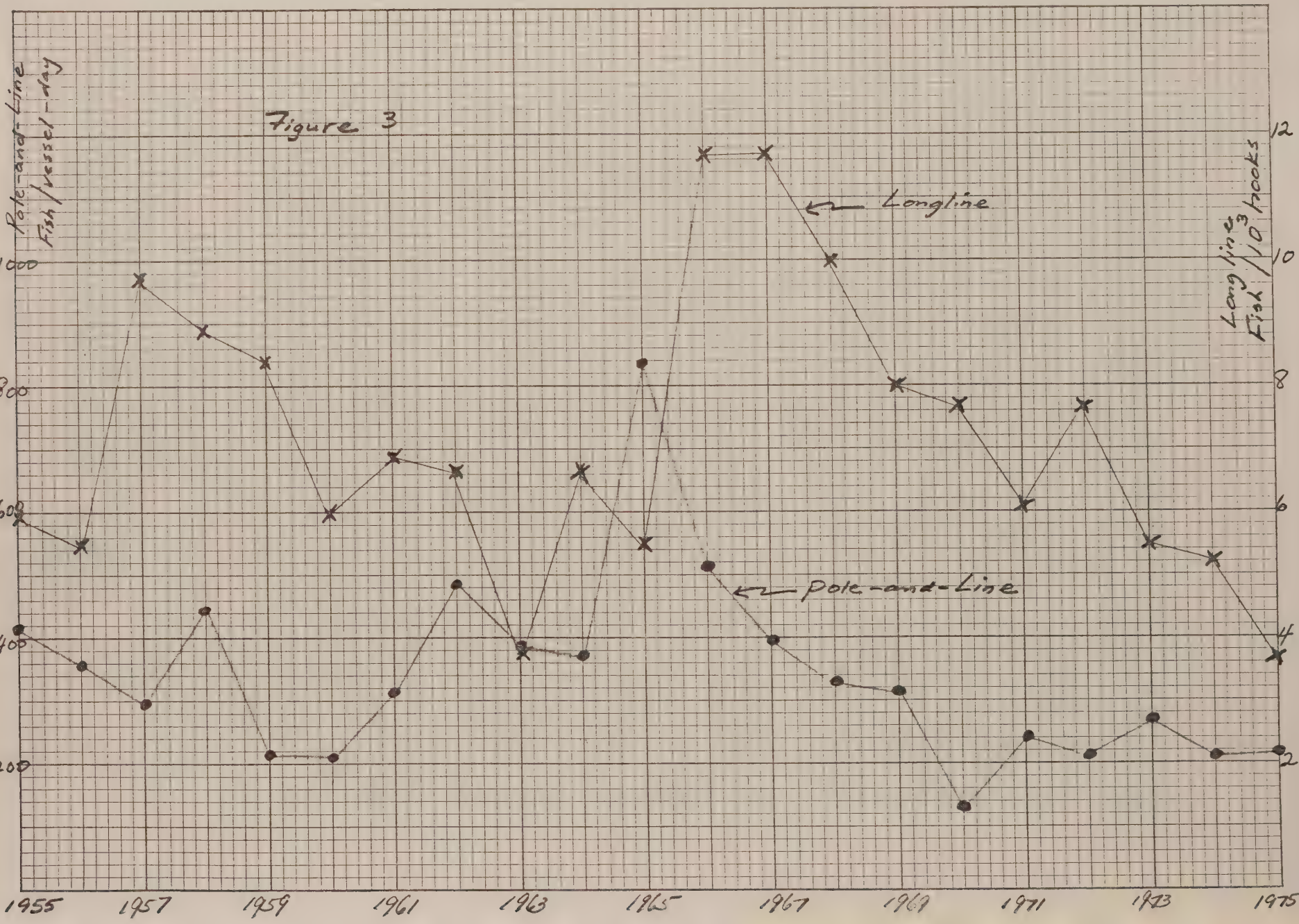


Figure 2.--Longline index areas.

K&E 7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Southwest Fisheries Center
Honolulu Laboratory
P. O. Box 3830
Honolulu, Hawaii 96812

TO ALL BILLFISHERS:

And so passes another outstanding Hawaiian International Billfish Tournament (HIBT) into history. The National Marine Fisheries Service (NMFS) has sent observers to the latest 17 of the 20 tournaments to gather biological data on game fishes, billfishes in particular. After the fishing and associated activities are over, we of the Honolulu Laboratory analyze the data and issue a report on the biological and statistical aspects of the tournament.

Before proceeding with the report, I would like to acknowledge all of you billfishers for your cooperation and support. It was your permission to allow us to inspect your fish and your faithful reporting at the radio round-ups that made it possible for Bob Humphreys and I to get the job done. Our sincere thanks also go to the tournament officials and community volunteers who assisted us in the data collecting. Peter Fithian and James Sutherland did their usual excellent job in the planning stages so that we could get right to work without a lot of worrisome preliminaries. Beverly and Phil Parker and Carol Zuzak gave us invaluable assistance at the radio round-ups. Colleen Bryant went out of her way to provide us with the data from the catch reports. Our work at the pier was certainly made easier by Jack Fischer. He could always be counted on for anything we needed and for setting up the equipment. Above all, special thanks to Chris Mason who assisted us with handling the numerous day to day details.

THE CATCH

Befitting the milestone of the 20th year of HIBT, the catch of billfish reached record breaking levels. The official tournament catch was 105 blue marlin, 2 striped marlin, 9 shortbill spearfish, and 43 ahi (yellowfin tuna) (Table 1). New HIBT records established are the number of blue marlin, the number of shortbill spearfish, and the total number of billfish (116). The catch is even more outstanding when one considers that in 1975, the previous record breaking year, there were 79 teams compared to the 65 teams this year. In fact the teams this year not only caught more billfish but caught more fish per team than the teams of 1975. The teams of 1978 beat the teams of 1975 by the diameter of a gnat's antenna...2.446 to 2.443 fish per team.

The largest blue marlin weighed 665 lb. The smallest was almost a tenth of the largest at 65.5 lb. The average weight of the blue marlin was 206.3 lb. The weights of the ahi ranged from 103.5 to

to 234 lb and averaged 164.4 lb. The nine shortbill spearfish ranged from 27 to 43 lb and averaged 33.9 lb. The two striped marlin weighed 35 and 42 lb.

FISHING AREAS

Year after year most of the fishing effort is concentrated in the same nine areas. This year was no exception; 96% of the effort was concentrated in those areas. The nine areas listed in order of number of boat-hours expended in them are: Juliet (375 boat-hours), Kilo (354 boat-hours), Sierra (312 boat-hours), Tango (250 boat-hours), Uniform B (186 boat-hours), India (172 boat-hours), Uniform A (163 boat-hours), Lima (149 boat-hours), and Victor (119 boat-hours). Only those areas with over 100 h of effort are considered in the analysis.

The strike rate for all areas combined was 0.20 strike per boat-hour. Table 2 lists the areas and their strike rates. Area Victor had the best strike rate by far with 0.39 strike per boat-hour. Areas India and Uniform B followed with 0.24 and 0.23 strike per boat-hour, respectively. The best strike rate for an area in 1977 was 0.22. The strike rate this year for all of the heavily fished areas was considerably better than last year. Figure 1 shows the areas categorized according to strike rates.

Table 3 summarizes the catch by area, species, and date. The best areas for blue marlin were Sierra (23), Kilo (20), Juliet (15), and Uniform B (14). When the areas are ranked by number of blue marlin per boat-hour of fishing (Table 2) Uniform B was best. It was followed by Sierra, India, Kilo, and Victor. In a billfish tournament where the point system is based on the weight of the fish, perhaps a more interesting variable to look at is the number of pounds per boat-hour (Table 2). In this case Sierra edged out Uniform B as the top area but the other top seven areas remained in the same order. Of the 10 largest blue marlin caught, 3 were caught in Uniform B, 3 in Sierra, and 1 each in India, Juliet, Kilo, and Victor.

The best areas for ahi were Victor, Uniform B, Kilo, and Sierra.

Area Alpha deserves special mention. Slightly more than 5 boat-hours of effort were spent in it. In that time one blue marlin and two ahi were caught for 62.6 lb of blue marlin per boat-hour and 52.5 lb of ahi per boat-hour.

SEX

Male blue marlin have outnumbered females at all HIBT tournaments except one since we started data collecting 16 years ago (Table 4). The males ran true to form this year. Of the 102 blue marlin examined 80 were males and 22 were females for a male:female ratio of 3.6:1.

As I mentioned in my report for HIBT 1977 catch rates of blue marlin were highly correlated with the number of males caught and independent of the number of females caught. The numerous males and high catch rate of this year strengthened that correlation.

TACKLE, TIME, AND TIDE

Fifty-three blue marlin were caught on 24-kg (50-lb) test line and 52 on 36-kg (80-lb) test line. The ahi catch was almost as closely divided: 40 on 24-kg test line and 43 on 36-kg test line. Blue marlin caught on 24-kg line averaged 193.5 lb compared to an average weight of 219.3 lb for those caught on 36-kg line. On the other hand, ahi caught on the lighter line outweighed their heavier line counterparts 164.8 lb to 156.3 lb per individual. The largest blue marlin was caught on 24-kg line and the smallest on 36-kg line.

For 3 consecutive years beginning in 1975 the 11 a.m. to noon hour was the best for blue marlin. This year the 9-10 a.m. hour was slightly better than other times (Figure 2a), especially in area Sierra where seven were caught during that period. More ahi were caught between 2 and 3 p.m. than any other hour (Figure 2b). Other ahi catches were fairly evenly distributed throughout the fishing day except for the first hour.

Strike rates (number of strikes per boat-hour) were highest during the rising tide on the first, second, and fifth days of fishing (Figure 3). On the third and fourth days strike rates were best during low tide and the strike rates during the rising tide were almost equal to that at low tide. Except for the second day the period of lowest strike rates was at high tide or just before it. Area Victor, on the contrary, exhibited the highest strike rates during high tide. The strike rates in Victor during this period were two to four times higher than the average strike rate. Because of its distance from the starting point area Victor did not have any fishing effort during low tide which occurred at the beginning of the fishing day.

MARLIN DIET

Like other years the principal items found in marlin stomachs this year were tunas, opelu, and squid. Opelu occurred in a much greater percentage of the stomachs (56%) than usual (18%-34%). The list of the different species of fish found in the stomachs (Table 5) was roughly 50% longer than usual. None of the species was unusual; that is, all of them have been found in marlin stomachs before, at one time or another, but not all together in the same tournament.

Ten of the 96 stomachs examined were empty, that is, completely devoid of food. An interesting fact about the empty stomachs is

that seven of them came from females. This means that 32% of the female blue marlin had empty stomachs compared to only 4% of the males. Does this mean that the large females are becoming weight conscious and fasting?

ABOUT OTHER SUBJECTS

In March 1978 Walter Matsumoto of the Honolulu Laboratory anchored two floating platforms in Kona waters as part of a fish aggregating experiment. One was positioned on the border of Kilo and Juliet and the other in India. I suspect that the platform at Kilo and Juliet is the reason that these areas were the leading areas in fishing effort during the tournament. The platforms have been so effective in attracting fish that several fishermen from Kona had predicted that there would be traffic jams around the platforms during the tournament. I don't know if their prediction materialized but areas Kilo and Juliet did have the most fishing effort during the tournament.

Dorsal fin rays from 22 blue marlin over a range of sizes were collected during this HIBT. We will analyze these to see if they have any markings which can be used as age indicators. If so they will be used to verify present growth rate information which is an important statistic in determining conservation strategy. Also collected for growth rate studies were four small mahimahi found in blue marlin stomachs. These specimens, 15-25 cm (6-10 in.) in length, were a fortunate find because they nicely fill in an important size gap for our growth rate studies.

Among the fish that you caught were two abnormalities I had not seen before. An ahi had two anal fins. One was a normal fin and the other a vestigial one. The other abnormality was a fist-size tumor in the stomach of a blue marlin. Unlike other recent years we did not find any stomach ulcers in the blue marlin, so it looks like conditions in the marlin world must be improving.

Allow me to close on a personal note. In the 5 years I have worked at HIBT, many of you have become my friends. I wish to acknowledge that your friendship has enriched my life. I look forward to HIBT as that special time in the year when we get together again. Until August 1979,

Aloha,

Heeny S. H. Yuen

Heeny S. H. Yuen
Leader, Recreational Fisheries

Attachments

September 21, 1978

Table 1.--Numbers of qualifying game fish landed and teams fishing during Hawaiian International Billfish Tournaments, 1962-78.

Year	Blue marlin	Black marlin	Striped marlin	Shortbill spearfish	Sailfish	Yellowfin tuna ≥100 lb	Total qualifying fish	Number of teams	Number of boat-days fishing per fish[1]
1962	30	1	--	--	1	19	51	68	6.7
1963	19	2	1	--	--	26	48	72	7.5
1964	31	--	1	--	--	2	34	69	10.1
1965	47	--	--	--	--	9	56	78	6.9
1966	26	3	2	--	--	7	38	72	9.5
1967	63	--	1	--	--	18	82	68	4.2
1968	36	2	4	--	--	4	46	85	9.2
1969	32	1	--	--	--	4	37	75	10.1
1970	91	--	2	--	2	14	109	73	3.3
1971	41	--	3	1	--	47	92	77	3.4
1972	77	--	--	--	--	11	88	59	3.4
1973	76	--	1	3	1	17	98	61	3.1
1974	66	2	1	6	--	37	110	64	2.9
1975	104	--	2	8	--	79	193	79	2.0
1976	47	1	3	5	--	32	88	74	4.2
1977	71	--	1	1	--	14	87	73	4.2
1978	105	--	2	9	--	43	159	65	2.0

[1]Nine-hour fishing days, 1962-73; 8-h days, 1974-78.

Table 2.--Strike and catch rates by area, Hawaiian International Billfish Tournament, 1978.

Area	No. of strikes / Boat-hour	No. of blue marlin / Boat-hour	Pounds of blue marlin / Boat-hour	No. of ahi / Boat-hour	Pounds of ahi / Boat-hour
India	0.24	0.058	13.2	0.000	--
Juliet	0.19	0.040	7.9	0.019	2.7
Kilo	0.21	0.057	11.0	0.023	4.1
Lima	0.14	0.013	3.4	0.007	1.3
Sierra	0.20	0.074	16.8	0.019	4.1
Tango	0.19	0.036	6.1	0.016	2.2
Uniform A	0.18	0.018	2.9	0.018	2.6
Uniform B	0.23	0.075	16.1	0.027	4.1
Victor	0.39	0.051	9.9	0.051	7.9

Table 3.--Number of fish caught by species, area, and date, Hawaiian International Billfish Tournament, 1978.

Date 1978	Area											
	A	B	I	J	K	L	M	S	T	UA	UB	V
Blue marlin												
July 31	--	--	1	--	5	--	--	9	1	1	1	2
August 1	--	--	--	4	2	--	1	6	2	1	3	2
2	--	1	--	2	2	--	--	3	1	1	1	--
3	1	--	4	4	7	1	--	4	2	--	5	1
4	--	--	5	5	4	1	--	1	3	--	4	1
Sum	1	1	10	15	20	2	1	23	9	3	14	6
Average weight (lb)	335.0	122.0	226.8	198.1	194.5	257.3	127.0	228.2	169.7	159.7	214.5	196.3
Ahi												
July 31	--	--	--	4	3	1	--	4	1	1	2	2
August 1*	1	--	--	1	1	--	--	2	--	1	--	4
2	--	--	--	--	1	--	--	--	2	1	--	--
3	--	--	--	1	1	--	--	--	1	--	--	--
4	1	--	--	1	2	--	--	--	--	--	3	--
Sum	2			7	8	1		6	4	3	5	6
Average weight (lb)	140.5			146.7	179.9	188.0		212.3	136.0	142.7	153.9	156.1
Shortbill spearfish												
July 31	--	--	1	--	--	--	--	--	1	--	--	--
August 1*	--	--	--	--	--	--	--	--	--	1	--	--
2	--	--	--	--	2	--	--	--	--	--	--	1
3	--	--	1	--	--	1	--	--	--	--	--	--
Sum			2		2	1			1	1		1
Average weight (lb)			40.5		36.5	28.5			33.0	27.0		35.0
Striped marlin												
August 2	--	--	--	1	--	1	--	--	--	--	--	--
Weight (lb)				35		42						

*One fish caught in unspecified area.

Table 4.--Sex ratios for blue marlin examined from Hawaiian International Billfish Tournaments, 1962-78.

Year	Number of males	Number of females	Ratio males to females
1962	16	7	2.3:1
1963	13	6	2.2:1
1964	14	12	1.2:1
1965	35	8	4.4:1
1966	16	8	2.0:1
1967	51	13	3.9:1
1968	24	10	2.4:1
1969	23	8	2.9:1
1970	63	14	4.5:1
1971	21	9	2.3:1
1972	64	8	8.0:1
1973	47	21	2.2:1
1974	46	14	3.3:1
1975	70	16	4.4:1
1976	7	37	0.2:1
1977	41	25	1.6:1
1978	80	22	3.6:1

Table 5.--Stomach contents of blue marlin, Hawaiian International Billfish Tournament, 1978.

Food items	Date and number of stomachs containing listed food items					Percent occurrence
	July	August				
	31	1	2	3	4	
Fish						
Tunas, Scombridae	8	8	5	14	12	49.0
Skipjack tuna	4	5	4	6	7	27.1
Other tunas	5	5	4	12	10	37.5
Jacks, Carangidae						
Opelu	4	10	4	21	15	56.3
Akule	--	--	--	1	--	1.0
Spiny puffer, Diodontidae	2	3	2	3	6	16.7
Mahimahi, Coryphaenidae	3	3	--	--	1	7.3
Snake mackerel, Gempylidae	1	--	--	4	1	6.3
Triggerfish, Balistidae	--	1	1	1	2	5.2
Aweoweo, Priacanthidae	--	--	1	--	3	4.2
Goatfish, Mullidae	--	--	--	1	3	4.2
Butterflyfish, Chaetodontidae	1	1	--	--	1	3.1
Squirrelfish, Holocentridae	--	1	1	1	--	3.1
Lancetfish, Alepisauridae	--	--	2	--	--	2.1
Sand lance, Ammodytidae	--	2	--	--	--	2.1
Flyingfish, Exocoetidae	1	--	--	--	--	1.0
Puffer, Tetraodontidae	1	--	--	--	--	1.0
Snipe eel, Nemichthyidae	1	--	--	--	--	1.0
Antigonia, Antigonidae	--	1	--	--	--	1.0
Needlefish, Belonidae	--	--	1	--	--	1.0
Ocean sunfish, Molidae	--	--	1	--	--	1.0
Cowfish, Ostraciidae	--	--	1	--	--	1.0
Surgeonfish, Acanthuridae	--	--	--	--	1	1.0
Unidentified fish	3	5	2	10	9	30.2
Invertebrates						
Squid, Loliginidae	8	12	6	12	9	49.0
Octopus, Octopodidae	--	--	1	--	--	1.0
Empty or everted stomachs	4	5	3	3	2	17.7
Number of stomachs examined	17	21	10	26	22	
Total: 96						

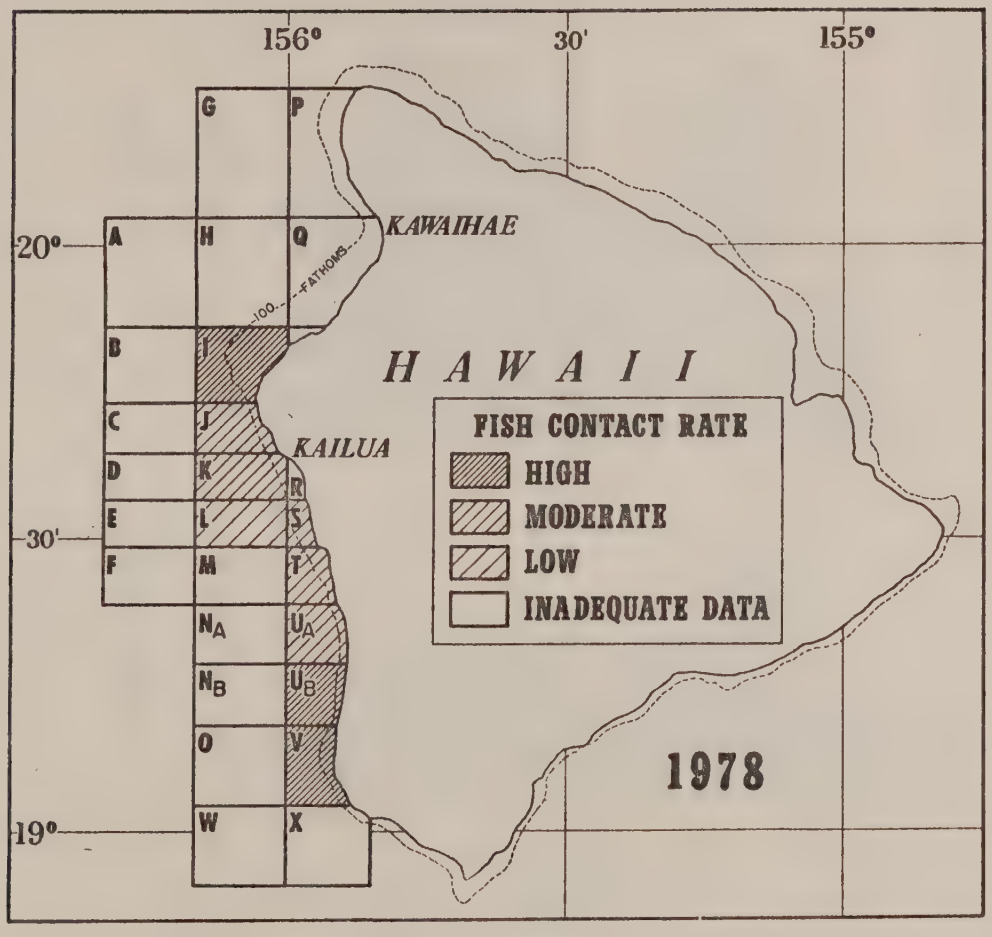


Figure 1.--Strike rate in various fishing areas.

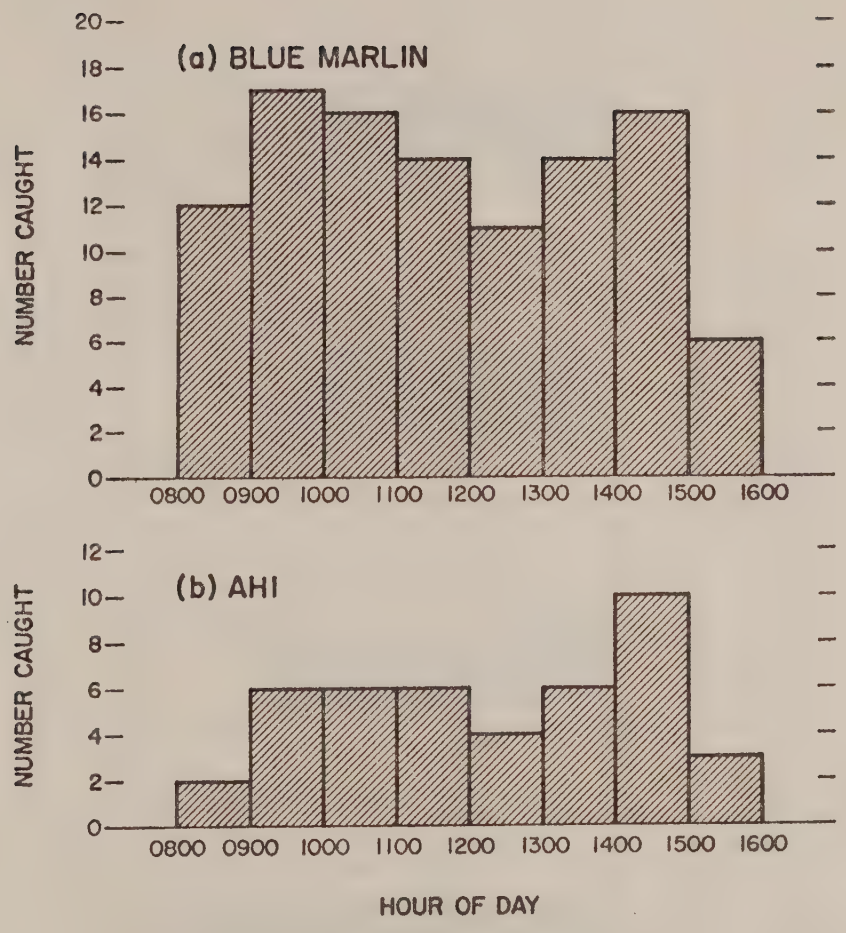


Figure 2.--Fish catch throughout the day by hours.

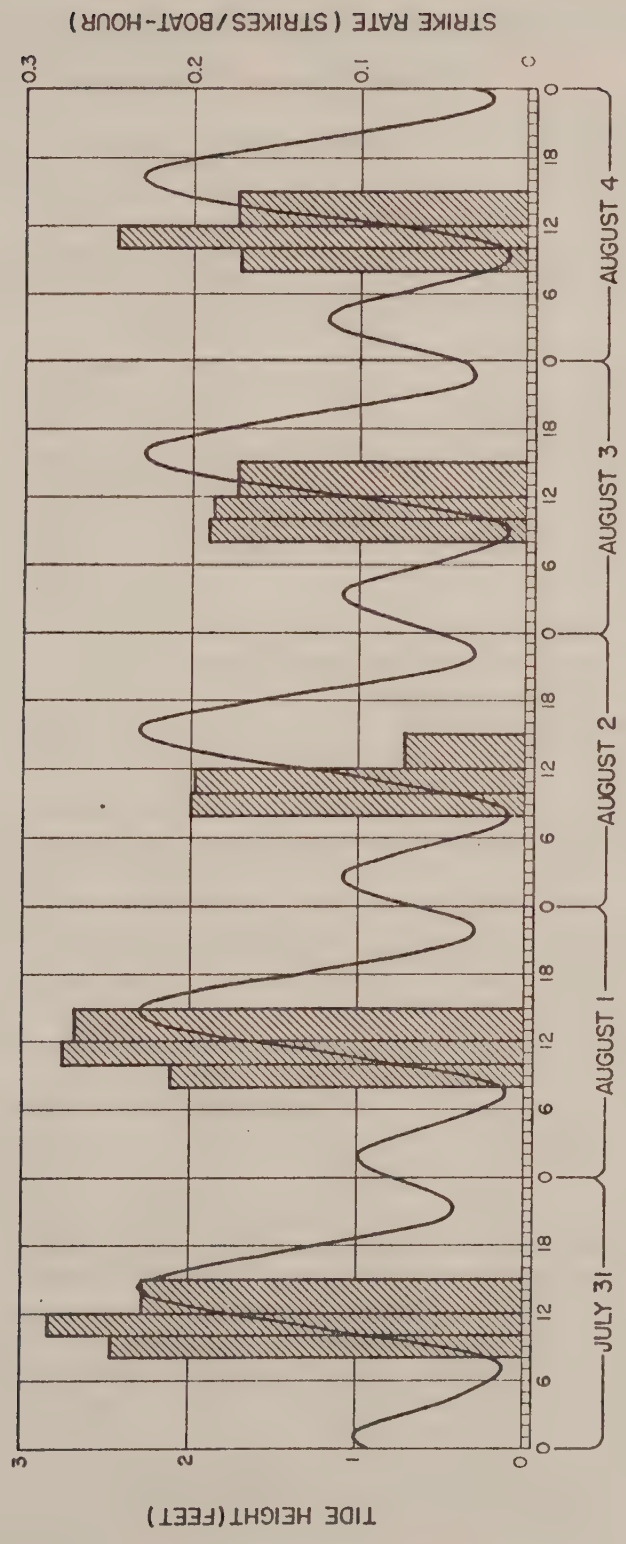


Figure 3.—Strike rates and tide cycle, Hawaiian International Billfish Tournament, 1978.

THE BILLFISHER

HAWAIIAN INTERNATIONAL BILLFISH ASSOCIATION NEWSLETTER

2923 MAKALEI PLACE, HONOLULU, HAWAII 96815

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VOLUME III Number 5

DECEMBER 1978

The Annual General Membership meeting of the Hawaiian International Billfish Association was held December 4, 1978, at the Ala Moana Americana Hotel, Honolulu, Hawaii.

The Nominating Committee asked Governors Franich of California, Goadby of Australia, Marr of the Philippines and McIntosh, Morioka and Rizzuto of the Island of Hawaii (all whose term of office expired December 31, 1978) to stand for re-election and they agreed to do so. Governor Young of the Island of Hawaii, whose term also expired, chose not to stand for re-election because of the press of business.

There were 312 ballots cast and recorded at the meeting, and the entire slate was re-elected for a 3 year period.

At a Governors Meeting on November 4, 1978 the following persons were elected to serve as Commissioners in 1979: Tom Armstrong; Gordon Bartsch; Colleen Bryant; Ralph Conner; Jeff Fay; Jack Fischer; Richard Hancock; Hank Hart; Jo Ann Hart; John Jordan; Rick Larsen; Harry Lyons; Jerry Panzo; Bev Parker; George Parker; Kathleen Pearson; Al Penrose; Ray Salley; Walter Stuefloten; Gene Wilhelm; Hal Wood.

All Governors and Commissioners of the Association contribute their services without remuneration of any kind and the fine job they do is greatly appreciated.

NEWS OF BILLFISHERS

Ed Jensen, a charter member of the Association and an outstanding angler, passed away since our last newsletter. Many of you will remember Ed and the Mardi J II from the HIBT in which he fished from 1969 to 1976 and gathered his share of trophies. We will miss him and we offer our sincere sympathy to his wife Mardi and his family.

For those of you in Hawaii, Leo Langomazino of Tahiti will be in town for the next several months undergoing a series of treatments for kidney problems. He is due to arrive next week and we'll be able to tell you where he will be staying after he is settled.

Becky Campos, wife of Tony who fishes the HIBT with the Pajaro Valley Gamefishing Club from Watsonville, California, won the Cortez Pacific Fishing Tournament held in early November at the tip of Baja California, Mexico. Her winning fish estimated to be more than 800 pounds gave here the title over 31 expert fishermen. She then teamed up with Tony who caught a marlin estimated at 350-400 lbs to win the couples trophy. Congratulations The Tourney is a light tackle catch and release competition and Mrs. Campos fought her fish for 2 hours on 20# test line before getting it up to the boat to qualify it as the winner. Maybe Becky should be on the Pajaro Valley team in '79?

Red Top California's Ray Flanagan has added a 6' 1" Sturgeon to his world-famous exhibit of mounted fish. If you are in his area, get Red to tell you the story of one of the strangest catches on record.

cont'd.....

COMMEMORATIVE ALBUM

Back in the early part of 1978, Sonny Burke, Hollywood record producer, musician and avid Billfisher, offered to select and produce an anthology of Great Hawaiian Music by the finest artists. Sonny has fished the HIBT for the past 11 years and he has done this as a labor of love to commemorate the Tournament's 20th year - and to bring together Hawaiian music never before available in one collection.

Much time and much effort on Sonny's part has been expended since the inception of the idea, and a two-record album of finest quality is now available to members and friends of HIBA and PGF. The Board has voted to assign all proceeds to the Pacific Gamefish Foundation and has set a special price of $25 for the unique commemorative album. Production, packaging and mailing costs are expected to be $8, so purchasers will be eligible for a $17 deduction against United States Income Tax for each album purchased.

A special mail order envelope is enclosed. We have indicated a normal 4 to 6 week delivery, but we will do our best to get your orders to you much sooner. Please be sure to make checks payable to Pacific Gamefish Foundation (PGF is sufficient).

SCIENTIFIC REPORT - 1978 HIBT

The National Marine Fisheries Service Report on the 20th Annual HIBT, prepared by Scientist Heeny Yuen, accompanies this Billfisher. Heeny has been preparing similar reports for the past 5 years and the information compiled for the 1978 Tournament is especially interesting. He compiles such statistics as strike and catch rates, boat-days of fishing per fish caught, correlation between strike rate and tide cycle and much more information of benefit to game fishermen. The reports have become the "Bible" for competitors in the HBT and the HIBT.

Heeny has one piece of information of value to all who catch big fish - how to quiet a monster if brought aboard green and full of fight. Place a towel, sack or other covering over the eyes and the fish will lie quietly!

The NMFS has been using a covering for years to quiet the big fish while a tag and/or a transmitter is fastened to it before release. Try it. It may save many a fighting chair and fish box - to say nothing of feet, arms and assorted portions of mortal anatomy.

UPDATE ON PRELIMINARY MANAGEMENT PLAN FOR PACIFIC BLUE MARLIN AND OCEANIC SHARKS

In part because of the information gathered during public hearings at the 1978 HIBT, the NMFS has revised its proposed PMP to include estimates of Optimum Yield (OY) by region rather than Pacific-wide. In addition, for Hawaii and Guam a reserve of 20% of the OY will be created to allow for expansion of fishing in those areas. The reserve principle means that there will be no surplus of Pacific Blue Marlin available to foreign vessels in either Hawaii or Guam.

In another change, Mahi Mahi and Ono are included in the management plan as well as billfish and sharks.

We are still attempting to have the non-retention zone for Billfish moved to the maximum of 200 miles around Hawaii from its proposed limit of 100 miles on the basis that foreign fishing for billfish, if concentrated around Hawaii even for a short period, could seriously affect the Marlin sportfishing industry and the recreational catch. In addition, we are still not convinced that Pacific-wide catch figures now available for Pacific Blue Marlin are accurate enough to declare the species "overfished". As Chairman of the Billfish Advisory Panel and your Executive Director, we have the opportunity and obligation to testify at all Public Hearings and to take part in many of the planning sessions. We are happy to do this in the interest of all recreational fishermen. More in the next Billfisher.

ALOHA BILLFISHERS,

J.W. Sutherland
Executive Director

ECONOMIC FEASIBILITY OF LOBSTER FISHING IN THE NORTHWESTERN HAWAIIAN ISLANDS

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(Revised April 1979)

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Easy Rider Too is a proposed fishing vessel which may be used to trap lobster, deep-sea handline, deep-sea longline, tender albacore trolling vessels, and conduct scientific charters. The vessel is scheduled to begin operations in the Northwestern Hawaiian Islands during 1980 and will be equipped to process and package frozen fish products at sea.

This report evaluates the economic efficiency of the vessel's lobster harvesting operations given the projections of investment cost, operating cost, and revenues as reported by the firm's investors. The economic feasibility of the investment is based on a discounted cash flow analysis for different combinations of discount rate, sustainable catch rate, average lobster weight, and ex-vessel price. The analysis abstracts from the other possible uses of the vessel which may, of course, affect the feasibility of the lobster operations.

Federal regulations under the Fishery Conservation and Management Act of 1976 may include minimum legal carapace lengths, among other regulations, which will influence legal catch rates, average sizes and thus, ex-vessel prices. The results of this report indicate that for a wide range of average lobster sizes and a wide range of discount rates, the minimum efficient catch rate is between 1 and 2.5 lobster per trap-day. The feasibility of the operation may be sensitive to a number of possible marketing constraints as discussed in the concluding remarks.

Recent developments in the Hawaii lobster fishery reflect the fact that increased utilization of the lobster resources requires fishermen to sell the product in markets other than Hawaii's traditional fresh fish market. Given the current levels of production, operating costs, and level of demand, it is not feasible to expand production of the live spiny lobster product in Hawaii. To increase utilization of the lobster resources, new vessels are processing and freezing lobster tails for the large restaurant markets in Hawaii and California which import similar products from Australia, New Zealand, and South America. The proposed vessel, Easy Rider Too, will represent the largest new addition to Hawaii's lobster fleet.

Discounted cash flow. Estimating the feasibility of lobster fishing begins with total revenue during the i^{th} period, R_i, which will vary for changes in the catch rate, γ_i (number of lobster per trap-day) and the average lobster size, σ_i (pounds per lobster tail). Total production of the firm is relatively small, such that it does not influence the market price. However, the price per pound may vary by the size of the fish. The size-price relationship may be due to the different processing efficiency of various fish sizes as in raw tuna for canning; or to different consumer preferences for various fish sizes as in the lobster market. Price, P_i (γ_i) (dollars per pound for lobster tail), is given for each average lobster size. Associating a unique price to a catch with a particular average lobster size assumes a catch with that average lobster size has a

unique size distribution. Fishing effort, E_i (number of trap-days), which may vary each period is constant in the analysis. Total revenue is written as

$$R_i = E_i \gamma_i \sigma_i P_i (\sigma_i) \tag{1}$$

Subtracting total operating costs, C_i, and depreciation, D_i, from total revenue yields taxable income. The combined state and federal income tax rate is t_i. The discount rate is δ_i. For i = 1, 2, ..., n, the discounted cash flow from period 1 to n-1 is

$$DCF_{1,\ n-1} = \sum_{i=1}^{n-1} \left[\frac{\left((R_i - C_i - D_i)\ (1 - t_i)\right) + D_i}{(1+\delta_i)^i} \right] \tag{2}$$

Upon termination of the investment, the cash flow at the end of the n^{th} period is increased by the operating capital and the scrap value of the capital equipment. Represented as fractions of depreciable capital, I, are operating capital, f, and scrap value, s. The discounted cash flow from all n periods may then be written as

$$DCF = DCF_{1,\ n-1} + \frac{\left((R_n - C_n - D_n)\ (1 - t_n) + D_n\right) + I(f+s)}{(1 + \delta_n)^n} \tag{3}$$

Using the notation for depreciable capital and scrap value, the straight-line method of depreciation is

$$D_i = \left(I(1-s)\right) / n \tag{4}$$

Net present value and the discount rate. The total capital investment minus the discounted cash flow equals the net present value, NPV:

$$NPV = I(1+f) - DCF \qquad (5)$$

This assumes that all investment occurs at the beginning of the first period. For an appropriately chosen discount rate, if NPV $\geq$ 0 then the investment is considered feasible. The discount rate an investor chooses reflects the returns of the best alternative investment and the risk of the investment. For example, if the best alternative investment yields 7% return and the proposed investment is considerably more risky, then the appropriate discount rate may be 12%. If NPV = 0 for a proposed investment using this discounted rate, then the investor is indifferent between the proposed investment and the best alternative investment. If NPV > 0 then the investor will prefer the proposed investment. Using the net-present-value criteria, then, the feasibility of an investment is relative to alternative investments with consideration for differences in risk between investments.[1]

Minimum feasible catch rates. To evaluate the impact of regulatory policies on the feasibility of an investment such as Easy Rider Too requires, in part, an estimate of the minimum feasible catch rate. Given the specific operating conditions of the investment, a schedule of minimum feasible catch rates is estimated for a range of discount rates using the net-present-value criteria. Estimates of

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[1]For a comprehensive survey and analysis of alternative investment criteria see Edward J. Mishan, Cost-Benefit Analysis, New and Expanded Edition, Praeger Publishers, New York, 1976, pp. 165-272.

depreciable capital, operating costs and effort were obtained from the investors and are presented in the confidential appendix. Effort is assumed to be constant. The variables n, t_i, f, and s are equal to 20 years, 0.50, 0.05, and 0.10, respectively. Again, it is assumed that changes in the total catch for Easy Rider Too do not influence the prices or catch rate. Under the net-present-value criteria, NPV $\geq$ 0, an average lobster size, and thus an ex-vessel price, will imply a minimum feasible catch rate for each discount rate. Four average lobster sizes (σ_i), 0.375, 0.500, 0.625, and 0.750, are evaluated with four associated ex-vessel prices $\left(P_i(\sigma_i)\right)$, 6.38, 6.00, 5.24, and 5.15, respectively. The prices are taken from Fishery Market News Report, National Marine Fisheries Service.

Figure 1 illustrates a schedule of minimum feasible catch rates for each average lobster size over a range of discount rates. The discount rate and minimum catch rate are positively related for each average lobster size. That is, the larger the discount rate used to evaluate the economic feasibility of the investment, the larger the required minimum feasible catch rate. On the other hand the average lobster size is inversely related to the minimum catch rate holding the discount rate constant. That is, a higher catch rate is required for the investment to be feasible if the average lobster size is smaller. Although price per pound is greater for the smaller size lobster, the increased revenue per pound is not enough to offset the decreased total weight due to the smaller average size. However, without the price differentials by lobster sizes, the four curves in Figure 1 would be

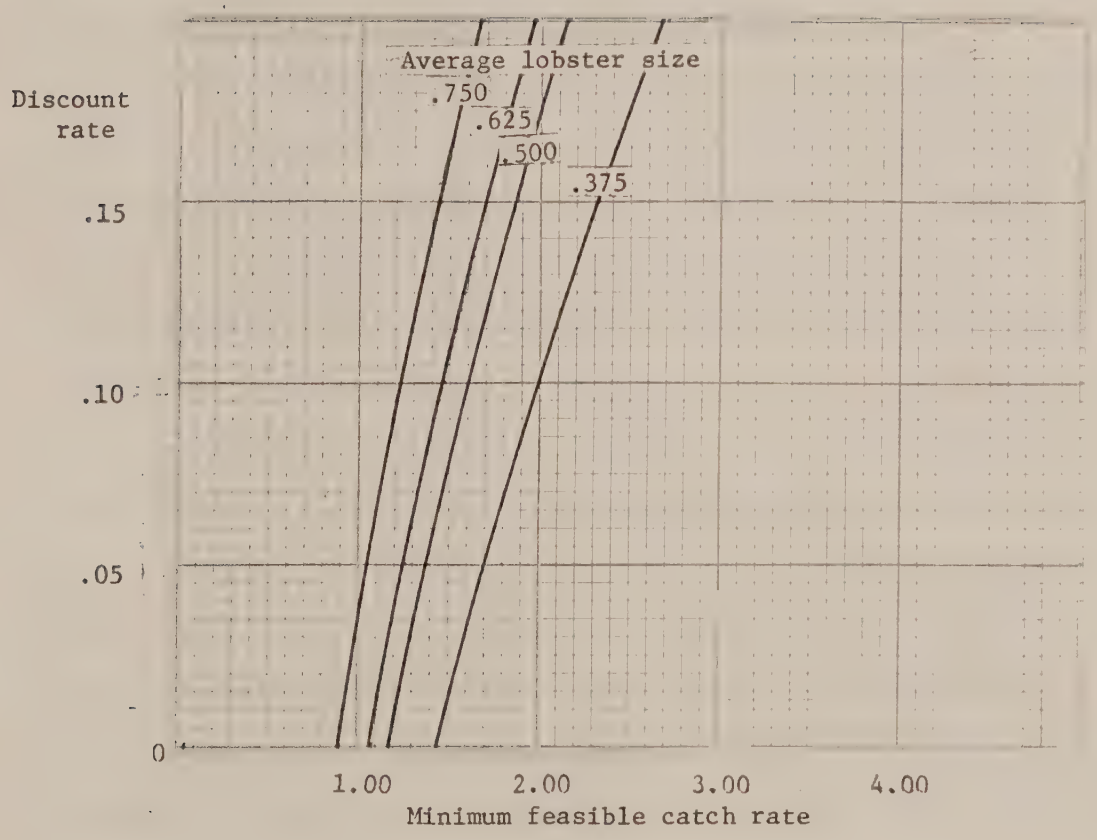

Figure--1. Minimum feasible catch rate by discount rate and average lobster size.

spread further apart. For a likely range of discount rates, say from 0.05 to 0.15, the minimum feasible catch rate is between 1.00 and 2.50 for all the average lobster sizes considered.

Unique marketing circumstances may cause shifts or discontinuities in the curves in Figure 1. For example, shippers or wholesalers may require a minimum total weight from a firm if all lobster tails are above some minimum size. Another peculiarity which may shift the curves is informal tying sales. Some major suppliers of lobster require the buyer to purchase larger size lobster tails in order to receive the smaller size tails. The investors express the concern that a minor supplier in the world market with a catch of only larger size lobsters may find it necessary to sell the larger tails below the existing market prices. For Easy Rider Too this may mean the shifting of the curves in Figure 1 to the right--increasing the minimum feasible catch rates. Currently the industry is uncertain about marketing conditions. Figure 1 must be revised as the fishery develops to account for the specific marketing peculiarities. Furthermore, the biology of the lobster stocks in the Northwestern Hawaiian Islands may be such that some parts of the schedules in Figure 1 are irrelevant. Nevertheless, the feasibility of the operation may be estimated for alternative regulatory policies which result in different legal catch rates and different average lobster sizes. The accuracy of such estimates will be greatly improved with more information on the long-term impacts on the stocks and therefore on the catch rates and average lobster sizes over time. Variations in these variables over time will give rise to unequal cash

flows between periods, when effort is constant, possibly improving the estimates of feasibility in this report.

Confidential Appendix

The following data was obtained from the investors. Depreciable capital, I, is $1,800,000, assumed to be purchased at the beginning of the first year. Effort, E, is 200,000 trap-days per year--5 trips per year for 40 fishing days each, fishing 1,000 traps per day. Operating cost, C, is $605,000 per year itemized in Appendix Table 1.

Appendix Table 1.--Estimated total annual operating costs.

Wages	$264,100
Fuel	49,700
Bait	90,000
Insurance	36,000
Food	25,200
Equipment replacement	5,000
Maintenance	75,000
Miscellaneous	60,000
Total	$605,000

PRELIMINARY ESTIMATES OF CATCH, SALES, AND REVENUE OF GAME FISH FOR THE FISHERY CONSERVATION ZONE AROUND THE MAIN HAWAIIAN ISLANDS, BY TYPES OF TROLL AND LONGLINE VESSELS AND BY SPECIES, 1976

By

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This report presents the best available data to satisfy specific requirements of the Pacific Billfish Fishery Management Plan until statewide surveys can be completed for Hawaii.

November 1978

The commercial and recreational vessels which fish for game fish around the main Hawaiian Islands can be classified into five groups: 1) Charter vessels. These vessels are available for hire to recreational fishermen. 2) Non-charter recreational-commercial vessels. These vessels are operated by individuals who have non-fishing occupations. Some of these fishermen sell part of their catch. 3) Fulltime commercial trolling vessels. These commercial boats fish by trolling as do the first and second groups. 4) Domestic longline vessels. 5) Foreign longline vessels.

The first section of this report estimates the number of vessels in each of the groups of vessels that troll for fish. The second section estimates the catch, sales and revenue for the same vessel groups generated by catches of billfish, tuna and other game fishes both in the Kailua-Kona area only and in the entire State of Hawaii. These estimates are then combined with the available longline catch data to estimate the total domestic catch and the total catch around the main Hawaiian Islands. The estimates given in this report are for 1976, the most recent year available, except where otherwise noted.

Estimation of the Number of Vessels Fishing for Game Fish in Hawaii. The following information on vessels in Hawaii is available from various sources: the number of commercial fishing boats in operation[1], the number of registered boats in the State of less than 5 net tons[2] and the number of documented vessels in the State greater than 5 net tons[3]. The combined figures for registered boats and documented vessels represent the total vessel population of the State. Additional information

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1. State of Hawaii. Department of Land and Natural Resources, Division of Fish and Game. Operating Units by Island and Gear, 1976-77 (unpublished).

2. State of Hawaii. Department of Transportation, Harbors Division. Report of Undocumented Vessel Registration, 1976, p. 3.

3. United States Coast Guard. Vessel Documentation Files, 14th Coast Guard District, U.S. Department of Transportation. U.S. Documented Vessels in Hawaiian Parts, 1976.

is obtained from two surveys completed for the National Marine Fisheries Service.[1] Table 1 presents the vessel classes involved and the estimates provided by each source.

The total number of vessels trolling for billfishes, tunas, mahimahi and ono in Hawaii is estimated by combining separate estimates for the charter recreational, non-charter recreational-commercial and commercial troller vessel classes. These three groups comprise the troller fishing fleet of Hawaii. The number of charter vessels is determined easily owing to separate vessel registration categories in both the Harbors Divison and Coast Guard listings. However, some vessels listed only participate in the charter fishing business on an occasional basis, and a few vessels active in the industry have been inadvertently omitted from the listings. The original count of 117 charter vessels for the State of Hawaii is amended to 102 vessels.[2]

Non-charter recreational-commercial fishing vessels are first estimated as an aggregated group. The report by Information Concepts indicated that 19% of the vessels in the State in 1973 participated in saltwater fishing at some time during the year. Assuming that this same percentage is applicable now, this implies that there were 3,220 vessels that fished on saltwater in 1976. Information from the Research Associates' Kailua-Kona survey report is usec to determine what proportion of these vessels troll for the relevant species. Corrections are made for improper listings and for vessels which do not fish for these species. It is estimated that 1,704 of the 3,220 total fishing vessels are in the non-charter trolling category.

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1. Information Concepts, Inc. Determination of the Number of Commercial and Non-Commercial Recreational Boats in the United States. Mimeographed. (prepared for NOAA/NMFS, 1973). 111 pp.+ appendices. And, Research Associates. A Study of Bioeconomics and Optimal Management Criteria for Utilization of Pacific Billfish, Module I. (Prepared for National Marine Fisheries Service, Honolulu Laboratory, 1977) 139 pp.

2. Official Program, 19th Hawaiian International Billfish Tournament (HIBT), Kailua-Kona, Hawaii, 1977. Ibid. 17th and 18th HIBT, 1975 and 1976.
Armstrong, Tom. Happy Time Deep Sea Fishing Charters, Honolulu and Keauhou, Hawaii (telephone interview, May 10, 1978).
Gaffney, Rick. Field editor, Hawaii Fishing News, Honolulu (telephone interview, May 10, 1978).

Table 1 -- Estimated number of vessels in Hawaii, by vessel classification and sources outlined in the text.

	Fish and Game [1]	Department of Transportation [2]	Information Concepts, Inc. [3]
Total vessels in State	-	16,947	15,321
Non-fishing vessels	-	15,761	12,335
Fishing vessels	1,437	1,186	2,986
Charter fishing vessels	-	117	-
Non-charter fishing vessels	-	1,069	-
Trolling and Charter Vessels	693	-	-

1. State of Hawaii. Department of Land and Natural Resources, Division of Fish and Game. Operating Units by Island and Gear, 1976-77 (unpublished).

2. State of Hawaii, Department of Transportation, Harbors Division. Report of Undocumented Vessel Registration, 1976, p. 3.

3. United States Coast Guard. Vessel Documentation Files, 14th Coast Guard District, U.S. Department of Transportation. U.S. Documented Vessels in Hawaiian Parts, 1976.

4. Information Concepts, Inc. Determination of the Number of Commercial and Non-Commercial Recreational Boats in the United States. Mimeographed. (Prepared for NOAA/NMFS, 1973). pp. 63, 67, 87.

The Research Associates' Kailua-Kona survey is again utilized to separate the private fishing vessel estimate into private commercial and non-charter recreational fishing vessel categories. A proportion relating the number of non-charter recreational fishing vessels to the total number of private registered trolling fishing vessels in Kailua-Kona is derived. This proportion is then projected to data for the Island of Hawaii and to the data estimated for the State. A similar extrapolation is made for the commercial trolling vessel class. Table 2 shows the estimate of the total number of trolling vessels in Hawaii in 1976, which is estimated to be 1,806 vessels.

Estimation of Catch, Sales and Revenue. Table 3 gives the summaries of the Kailua-Kona survey. The three vessel classes shown represent the major user groups involved in the trolling fishery. Table 4 lists the values of Table 3 projected to the entire State of Hawaii, based on the number of vessels in the State in each vessel class.[1] This extrapolation assumes that catch rates and fishing effort are the same for Kailua-Kona as for the State. In Table 5 the Total Kailua-Kona troller figures are the combined vessel classes on Table 3. Estimate I under Total Hawaii Trollers respresents a similar compilation of the data from Table 4. Estimate II is an alternate estimate of Statewide troller catch. This estimate is derived from a comparison of the Kailua-Kona troller survey data with similar data of the State of Hawaii Division of Fish and Game[2]. This comparison provides an index of the underestimation of catch and other data for each species by the Division of Fish and Game relative to the survey data. Assuming that Statewide data are underreported by the same proportion, Division of Fish and Game Statewide catch data for each species are increased by a factor of 7.36 for billfishes, 7.33 for tunas and 10.08 for other game fishes.

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1. See Table 2.

2. State of Hawaii. Department of Land and Natural Resources, Division of Fish and Game. 1976 Fish and Game Fishery Statistics -- Kailua-Kona Area (unpublished).

Table 2 -- Estimated number of vessels in Kailua-Kona, the Island of Hawaii and the State of Hawaii, by vessel classification, 1976.

	Kailua-Kona[1]	Big Island	State
Registered vessels	- - -	1,382[2]	16,947[3]
Registered fishing vessels	577*	1,075	3,220[4]
Registered trolling fishing vessels	426	730	1,704
Non-charter recreational-commercial trolling fishing vessels	386	661	1,544
Commercial trolling fishing vessels	40	69	160
Charter vessels	30	35	102
Total trolling fishing vessels	456	765	1,806

*Greater than 14 ft.

1. Research Associates. A Study of Bio-economics and Optimal Management Criteria for Utilization of Pacicic Billfish, Module I. (Prepared for National Marine Fisheries Service, Honolulu Laboratory, 1977.) 139pp. - plus appendices. (For all vessel classifications.)

2. State of Hawaii. Harbors Division. Department of Transportation. Report of Undocumented Vessel Registration, 1976. p. 3. (For registered vessels classification only.)

3. a) Ibid.
   b) United States Coast Guard. Vessel Documentation Files. 14th Coast Guard District, U.S. Department of Transportation. U.S. Documented Vessels in Hawaiian Parts, 1976 (Unpublished).

4. Information Concepts, Inc. Determination of the Number of Commercial and Non - Commercial Recreational Boats in the United States. Mimeographed. (Prepared for the National Oceanic and Atmospheric Administration/National Marine Fisheries Service, 1973.) p. 67.

Quantity sold was similarly adjusted by factors of 5.34 for billfishes, 6.35 for tunas and 6.46 for other gamefishes. New revenues were computed from the derived quantity sold values and average revenues from the Division of Fish and Game Statewide data.

Thus three estimates are available for the entire State of Hawaii: raw data from the Hawaii Division of Fish and Game, extrapolated Kailua-Kona survey data based on vessel class number (EstimateI) and adjusted Hawaii Division of Fish and Game data (Estimate II). The best estimate appears to be Estimate I, owing to the ability to separate out the user groups. Statewide estimates based on these vessel class extrapolations account for the differential catch rates and fishing efforts between the groups. These distinctions cannot be made using the Hawaii Divison of Fish and Game data or Estimate II.

Table 6 shows the catch and other data for the domestic longline fishery around the Hawaiian Islands. Total domestic catch is the combination of these longline data with Estimate I. Foreign longline catch is represented by Japanese data, since fishing around the main Hawaiian Islands by other foreign countries is negligible. Foreign catch data for 1976 are unavailable, so 1975 data are substituted with an assumption of constant catch between the two years. Catch of mahimahi and ono is also unavailable for foreign longliners. Domestic and foreign catches are combined to estimate the total catch around the main Hawaiian Islands.

Table 3 --Catch, sales, revenue, and average revenue by species, for three troller vessel types in Kailua-Kona, 1976.

Species	Charter				Private recreational-commercial				Private commercial			
	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average revenue ($/kg sold)	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average revenue ($/kg sold)	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average revenue ($/kg sold)
Blue marlin	94,834	73,572	27,221	0.37	42,565	24,939	15,545	0.62	12,085	11,178	6,587	0.59
Black marlin	5,770	4,846	1,751	0.36	11,690	5,110	4,368	0.85	7,144	7,001	5,994	0.86
Striped marlin	5,347	4,560	1,799	0.39	2,219	891	433	0.49	273	273	408	1.49
Other billfishes	2,088	1,309	945	0.72	2,981	647	1,036	1.60	1,006	811	766	0.94
Total billfishes	108,039	84,287	31,716	0.38	59,455	31,588	21,382	0.68	20,508	19,263	13,755	0.71
Ahi (large tunas)	41,806	33,315	51,931	1.56	127,687	96,079	191,361	1.99	286,144	284,521	621,970	2.19
Aku (skipjack)	12,412	386	575	1.49	17,251	3,050	4,378	1.44	2,541	1,161	1,970	1.70
Total Tunas	54,218	33,701	52,506	1.56	144,938	99,129	195,739	1.97	288,685	285,682	623,940	2.18
Ono (wahoo)	14,025	10,446	22,650	2.17	43,798	18,745	35,353	1.89	15,586	15,265	28,945	1.90
Mahimahi (dolphin)	8,913	5,534	15,296	2.76	9,886	5,122	13,158	2.57	6,946	6,509	21,440	3.29
Total ono & mahi	22,938	15,980	37,946	2.37	53,684	23,867	48,511	2.03	22,532	21,774	50,385	2.31
Grand total	185,195	133,968	122,169	0.91	258,077	154,584	265,632	1.72	331,725	326,719	688,080	2.11

Source: Survey questionnaires completed by Research Associates.

Table 4 --Catch, sales, revenue, and average revenue by species, for three troller vessel types in Hawaii, 1976.

Species	Charter				Private Recreational-commercial				Private Commercial			
	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average revenue ($/kg sold)	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average revenue ($/kg sold)	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average revenue ($/kg so
Blue marlin	322,436	250,145	92,551	0.37	170,260	99,756	62,180	0.62	48,340	44,712	26,348	0.59
Black marlin	19,618	16,476	5,953	0.36	46,760	20,444	17,472	0.85	28,576	28,004	23,976	0.86
Striped marlin	18,180	15,504	6,117	0.39	8,876	3,564	1,732	0.49	1,092	1,092	1,632	1.49
Other billfishes	7,099	4,451	3,213	0.72	11,924	2,588	4,144	1.60	4,024	3,244	3,064	0.94
Total billfishes	367,333	286,576	107,834	0.38	237,820	126,352	85,528	0.68	82,032	77,052	55,020	0.71
Ahi (large tunas)	142,140	113,271	176,565	1.56	510,748	384,316	765,444	1.99	1,144,576	1,138,084	2,487,880	2.19
Aku (skipjack)	42,201	1,312	1,955	1.49	69,004	12,200	17,512	1.44	10,164	4,644	7,880	1.70
Total Tunas	184,341	114,583	178,520	1.56	579,752	396,516	782,956	1.97	1,154,740	1,142,728	2,495,760	2.18
Ono (wahoo)	47,685	35,516	77,010	2.17	175,192	74,980	141,412	1.88	62,344	61,060	115,780	1.90
Mahimahi (dolphin)	30,304	18,816	52,006	2.76	39,544	20,488	52,632	2.57	27,784	26,036	85,760	3.29
Total ono & mahi	77,989	54,332	129,016	2.37	214,736	95,468	194,044	2.03	90,128	87,096	201,540	2.31
Grand Total	629,663	455,491	415,370	0.91	1,032,308	618,336	1,062,528	1.72	1,326,900	1,306,876	2,752,320	2.11

Source -- Table 2 and Table 3.

Table 5 — Catch, sales, revenue, and average revenue by species for Kailua-Kona Trollers and Total Hawaii Trollers, 1976.

Species	Total Kailua-Kona Trollers[1]				Total Hawaii Trollers							
					Estimate I[2]				Estimate II[3]			
	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average Revenue ($/kg sold)	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average Revenue ($/kg sold)	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average Revenue ($/kg sold)
Blue marlin	149,484	109,689	49,353	0.45	541,036	394,613	181,079	0.46	544,927	253,324	195,059	0.77
Black marlin	24,604	16,958	12,113	0.71	94,954	64,924	47,401	0.73	18,201	9,788	8,711	0.89
Striped marlin	7,839	5,724	2,640	0.46	28,148	20,160	9,481	0.47	408,296	177,849	158,286	0.85
Other billfishes	6,075	2,767	2,747	0.99	23,047	10,283	10,421	1.01	24,972	10,611	11,460	1.08
Total billfishes	188,002	135,138	66,853	0.49	687,185	489,980	248,382	0.51	996,396	451,572	373,516	0.81
Ahi (large tunas)	455,637	413,915	865,262	2.09	1,797,464	1,635,671	3,429,889	2.10	2,333,388	1,659,820	3,618,408	2.18
Aku (skipjack)	32,204	4,597	6,923	1.51	121,369	18,156	27,347	1.51	167,710	82,588	139,574	1.69
Total Tunas	487,841	418,512	872,185	2.08	1,918,833	1,653,827	3,457,236	2.09	2,501,098	1,742,408	3,757,982	2.16
Ono (wahoo)	73,409	44,456	86,948	1.96	285,221	171,556	334,202	1.95	411,768	185,835	650,423	3.50
Mahimahi (dolphin)	25,745	17,165	49,894	2.91	97,632	65,340	190,398	2.91	540,076	255,467	559,473	2.19
Total ono & mahi	99,154	61,621	136,842	2.22	382,853	236,896	524,600	2.21	951,844	441,302	1,209,896	2.74
Grand Total	774,997	615,271	1,075,880	1.75	2,988,871	2,380,703	4,230,218	1.78	4,449,388	2,635,282	5,341,394	2.03

1. See Table 3.
2. See Table 4.
3. See text.

Hawaii trollers and longliners, 1976, foreign longline catch, 1975, and total catch around the main Hawaiian Islands, 1976.

Species	Domestic Longline[1]				Total Domestic Catch[2]				Foreign[3] Longline	Total Catch Around Main Hawaiian Islands
	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average Revenue ($/kg sold)	Catch (kg)	Quantity sold (kg)	Revenue from sales ($)	Average Revenue ($/kg sold)	Catch (kg)	Catch (kg)
Blue marlin	7,598	7,598	12,089	1.59	548,634	402,211	193,168	0.48	5,399	554,033
Black marlin	190	190	443	2.33	95,144	65,114	47,844	0.73	321	95,465
Striped marlin	33,686	33,686	81,116	2.41	61,834	53,846	90,597	1.68	26,004	87,838
Other billfishes	3,652	3,652	5,537	1.52	26,699	13,935	15,958	1.15	13,441	40,140
Total billfishes	45,126	45,126	99,185	2.20	732,311	535,106	347,567	0.65	45,165	777,476
Ahi (large tunas)	129,503	129,503	384,502	2.97	1,926,967	1,765,174	3,814,391	2.16	---	---
Aku (skipjack)	13	13	22	1.69	121,382	18,169	27,369	1.51	---	---
Total Tunas	129,516	129,516	384,524	2.97	2,048,349	1,783,343	3,841,760	2.15	288,958	2,337,307
Ono (wahoo)	3,418	3,418	6,409	1.88	288,639	174,974	340,611	1.95	---	---
Mahimahi (dolphin)	7,466	7,466	30,003	4.02	105,098	72,806	220,401	3.03	---	---
Total ono & mahi	10,884	10,884	36,412	3.35	393,737	247,780	561,012	2.26	---	393,737*
GRAND TOTAL	185,526	185,526	520,121	2.80	3,174,397	2,566,229	4,750,339	1.85	334,128	3,508,525

1 State of Hawaii, Division of Fish and Game, Department of Land and Natural Resources. Fishery Statistics, Summary II, 1976 (Unpublished).

2 Combined Hawaii trollers (Estimate I) and Domestic longline.

3 Yong, M.Y.Y. and J. Wetherall, (title to be determined), SWFC Administrative Report No. 13H, 1978.

*Domestic only

Southwest Fisheries Center Administrative Report 25H, 1978
(Revised)

REPORT OF THE

THIRD NORTH PACIFIC ALBACORE WORKSHOP

HONOLULU, HAWAII

13-14 SEPTEMBER 1978

Edited by

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I. Introduction

The Third North Pacific Albacore Workshop was conducted at the National Marine Fisheries Service (NMFS) laboratory in Honolulu, Hawaii, on 13-14 September 1978. The event was part of a continuing informal arrangement established in 1974 between NMFS' Southwest Fisheries Center and the Far Seas Fisheries Research Laboratory, Shimizu, Japan, to promote and accelerate joint investigations into the biology, ecology, and population dynamics of North Pacific albacore, Thunnus alalunga. Two other workshops have been held; the first in Honolulu in December 1975 and the second at Shimizu in May 1977.

The third meeting was attended by scientists from the two principal agencies and by biologists representing the California Department of Fish and Game, the Oregon Department of Fisheries and Wildlife, the Washington Department of Fisheries, and Fisheries and Environment Canada. Participants are listed in Appendix A. Jerry A. Wetherall acted as chairman of the workshop. Norman W. Bartoo and Mark G. Pedersen were rapporteurs, assisted by Gary T. Sakagawa.

Richard S. Shomura, Director of the Honolulu Laboratory, welcomed the participants and reviewed the terms of reference for the workshop. He emphasized the growing need for international cooperation in research on highly migratory species and stressed the value of maintaining the close and productive ties between the Honolulu Laboratory and the Far Seas Fisheries Research Laboratory.

The chairman described the purposes of the workshop, which were:

(1) To review the status of the various North Pacific albacore fisheries during 1977 and 1978, to exchange fishery data, and to update basic statistical tables;

(2) to exchange views, ideas, and research results on a range of subjects related to albacore stock assessment and ecology, through the presentation and discussion of working papers;

(3) to produce this report containing the fishery review, the updated fishery statistics, summaries of the working papers, a current assessment of the North Pacific albacore resource, and recommendations for continued cooperative research.

Appendix B gives the agreed workshop agenda. A list of documents submitted to the workshop, including various data tables, statistical reports and working papers, is attached as Appendix C.[1]

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[1]Working papers were prepared solely for discussions at the workshop and were not intended for wide dissemination. Requests for copies should be directed to individual authors.

II. Review of Fishery Statistics

A. Trends in Catch

The estimated annual catches of North Pacific albacore from 1961 through 1977 are listed in Table 1 and plotted in Figure 1. The catches by Japanese vessels are compiled by the Fisheries Agency of Japan. Canadian catch statistics are gathered by Fisheries and Environment Canada. The statistics for the United States jig catch are derived directly from landings data furnished by California, Oregon, and Washington, on the assumption that all albacore caught by U.S. vessels are landed in one of these states. Estimates for the U.S. bait boat fleet reflect only the catch of those vessels submitting logbooks to the Inter-American Tropical Tuna Commission, but this includes most of the fleet. The balance is included with the U.S. jig catch. Excluded from the table is the catch taken in the last couple of years by bait boats and longliners of the Republic of Korea and Taiwan. This catch is unknown but it is considered to be only a small and insignificant fraction of the total North Pacific albacore harvest. Also omitted is a practically negligible catch by party boat anglers and other recreational fishermen in the U.S.

The general trend of the aggregate catch was upward over the 1961-76 period, the lowest catch being 42,185 metric tons (MT) in 1962 and the highest 122,804 MT in 1976. The catch records illustrate the increasingly dominant role of the Japanese pole-and-line fleet since it began a rapid expansion in 1971 (Table 2). Between 1971 and 1976 the Japanese pole-and-line catch increased from an annual average of about 25,000 MT to over 85,000 MT. In 1977, the total North Pacific albacore catch plummeted to 55,987 MT, due primarily to a sharp drop in the Japanese pole-and-line catch. However, the 1977 United States and Canadian landings were also substantially lower than in 1976, the United States jig landings being the lowest recorded since 1951. The estimated Japanese longline catch during 1977 was also less than in the previous year. While no specific figures were available for 1978, the Japanese pole-and-line catch through August was only slightly greater than in the previous year, and the United States jig catch, while showing improvement over the 1977 figure, was still expected to be below normal.

Workshop participants reviewed information and hypotheses bearing on the sudden drop in catch in the surface fisheries. There was considerable support for the idea that oceanographic conditions were primarily responsible. In particular, the weak development of frontal structure was thought to be a major cause of poor fishing conditions, both in the Japanese pole-and-line fishery in the western North Pacific and in the United States and Canadian jig and bait boat fisheries of the eastern North Pacific. While below-average availability and weak temperature fronts were considered the main limiting

factors in the eastern Pacific, in the case of U.S. vessels reduced catches were also attributed to a relatively high proportion of potential fishing days lost due to rough seas and other weather-related factors.

B. Trends in Catch Per Unit Effort (CPUE)

In each of the three major fisheries annual catch-per-unit-effort (CPUE) statistics were compiled over the 1961-76 period. Additional CPUE statistics for 1977 were available for Japanese pole-and-line vessels and U.S. jig boats (Table 3). The data for 1961-76 were normalized by dividing each year's CPUE by the average CPUE computed over the 16-yr period. Figure 2 and Table 3 present these normalized CPUE statistics. In none of the five sets of normalized CPUE data is the 16-yr trend significantly negative. In fact, the only significant regression is with the "adult area" longline CPUE, and here the long-term trend is positive. However, a linear model may not adequately describe changes in CPUE over the entire period.

Catch rates in the Japanese pole-and-line fishery between 1961 and 1969 showed a slightly declining trend, but then increased generally through 1976 with higher variation. In 1977 the actual pole-and-line CPUE (Table 3) dropped sharply to the lowest level in the 17-yr period. During the 1970's, as the pole-and-line fleet has grown, the northern and eastern boundaries in the fishing grounds have also expanded. More fishing effort has been exerted on albacore in the Kuroshio Front region, where the average size of albacore in the catch is less than it is further south.

The normalized catch rates for the U.S. jig fleet show relatively high variation from year to year, presumably reflecting changes in availability. Since 1961 there have been two periods of relatively high catch rates; 1962-63 and 1967-70. Catch rates during the 1970's have been generally below the long-term average and in 1977 the actual catch rate was the lowest recorded during the 17-yr period.

The remaining sets of CPUE statistics are from the Japanese longline fishery. When compiled over the entire albacore longline grounds the CPUE showed an increase from 1961 to 1966, then a decline from 1967 to 1971, followed by a rise to above-average catch rates in 1973 and 1974. Catch rates in 1975 and 1976 were below average. A different pattern is seen when CPUE statistics are examined over smaller segments of the North Pacific grounds. North of lat. 25°N the longline catch is composed of relatively young albacore, and the CPUE there has been below the long-term average during 7 of the last 8 years on record. In contrast to this is the trend in CPUE on the larger, adult albacore taken south of lat. 25°N. Here during the

same period, 1969-76, the CPUE dropped below average only 3 years out of 8.

In all of these series of statistics a crucial question is whether changes in CPUE reflect real changes in stock size or whether they are due to other events. In general, CPUE is a complex function of several factors, including the actual abundance or size of the harvestable albacore stock, the availability of albacore in a given fishing area, the degree to which albacore forage organisms are concentrated by thermal fronts and other oceanographic conditions, and the distribution of the fishing vessels relative to the fish. Some of these factors can be observed and measured; others cannot. For example, year-to-year changes in oceanographic conditions and fleet distribution may be charted, but no independent estimates of stock size or stock distribution are available.

In the case of the surface fisheries especially, CPUE is strongly affected by oceanographic factors such as the development of frontal structure, by spatial and temporal variations in effort distribution, and by fluctuations in year-class strength. While the effects of these factors are confounded in the CPUE statistics, there is considerable evidence that the reduced CPUE indices in 1977 were a result of abnormally weak development of temperature fronts. However, without additional information, particularly unbiased age-specific abundance indices, other causes cannot be ruled out. For example, fluctuations in recruitment might be a factor, since cohort analyses have shown a fourfold to fivefold variation in year-class strength.

Inconsistencies between the various sets of CPUE data described here appear to be systematic, rather than simply statistical in nature. The indices clearly represent different processes, and different combinations of effects and influences. Understanding the processes and determining which index, if any, is appropriate for measuring changes in stock size are critical issues in albacore stock assessment.

III. Presentation and Discussion of Working Papers

A. Population Dynamics and Resource Assessment

An assessment of the North Pacific albacore resource was made by Shiohama (WP-1) using the generalized production model and the computer program PRODFIT. The analysis was based on 1) annual normalized CPUE statistics, from 1965 to 1976, representing the Japanese pole-and-line and longline fisheries and the United States jig fishery, and 2) total catch statistics from the Japanese pole-and-line and longline fisheries and the combined eastern Pacific catches of the United States and Canada. The Japanese pole-and-line

statistics were separated into two sets, one representing the "Frontal Area" in the northern part of the fishing grounds, and the other representing the remaining region of pole-and-line fishing. The longline data were also divided into two sets, one from the region north of lat. 25°N where young albacore predominate and one representing the area between the equator and lat. 25°N, where larger, more mature albacore are taken. In fitting the production model Shiohama considered two cases with respect to the Japanese pole-and-line data; first, that the southern limit of the Frontal Area was fixed at lat. 35°N; and second, that this boundary shifted from year to year depending on oceanographic conditions. In each case the model was fitted using a range of shape parameters (the parameter "m" in the production model). There was little difference in the goodness of fit among different m values, owing to the absence of observations from the region of the production curve's right-hand limb. Considering all sets of data and assumptions, the maximum sustainable yield (MSY) of North Pacific albacore was judged to be in the range of 100,000-120,000 MT per year.

As an alternative to the standard production model analysis, which ignores age-structure, Wetherall and Yong (WP-5) considered the use of age-specific abundance indices and effective effort statistics to estimate vital parameters of albacore population dynamics and to predict stock size and catch. They described a simple technique which integrates available statistics on relative stock size and age composition and produces both steady state information for determining general harvest strategy and short-term predictions of abundance and catch for use in tactical planning. First attempts to apply the method to North Pacific albacore data over the period 1955-75 were unsuccessful as a result of statistical problems. These are being diagnosed and work on the model and its applications is continuing.

Whereas the aim of Wetherall and Yong was to forecast abundance and catch over the whole stock range, Shiohama (WP-2) reported Japanese efforts to predict albacore catches in their pole-and-line fishery alone. Japanese scientists have demonstrated a good relationship between the catch of 4-year-old fish by longliners and 5-year-olds taken by pole-and-line vessels a few months later [fish of the same year-class]. However, the practical application of this predictor will require speedier data processing procedures than are now available. Relationships have also been demonstrated between February albacore landings in Wakayama Prefecture and total annual albacore landings by the Japanese pole-and-line fleet, especially with data collected since 1971, when the fishery in the Frontal Area developed. This forecasting approach seems to require the "normal" development of the frontal grounds, because it failed in 1977 when the usual conditions in the Frontal Area did not materialize.

B. Fishery Oceanography and Biology

Laurs (WP-6) discussed several factors believed to be responsible for the low U.S. albacore catch and poor fishing conditions in 1977: 1) albacore were not as abundant or available as in 1976 off Oregon and Washington, perhaps due to a delay in the eastward summer migration, 2) albacore were more scattered than usual due to poorly developed upwelling fronts which concentrate albacore forage organisms, 3) despite fairly adequate concentrations of albacore south of San Francisco, many fish there seemed not to "bite" as readily as usual, and 4) the full potential of nominal fishing effort was not realized as a result of several periods of inclement weather and rough seas, which either kept vessels in port or made fishing difficult.

A paper by Kikawa (WP-3) dealing with fishing conditions in the Japanese pole-and-line fishery in 1977 and 1978 was presented by Mr. Shiohama and Dr. Hayasi. The abnormally poor conditions experienced in 1977, and again in 1978, were attributed to two factors: 1) below average availability of albacore resulting from unfavorable oceanographic conditions in the Frontal Area; it was shown that cold water masses at lat. 35°N, between long. 150°E and 170°E, had intruded much closer to the surface in 1977 than in 1976, reducing the area of preferred albacore habitat; 2) shifts in the age-structure of the albacore stock, resulting in a reduction of the average size of albacore in the catch. Four-year-old fish dominated the Yaizu market albacore landings from 1974 through 1976, but were overshadowed by 3-year-olds in 1977. It is expected that 2-year-olds will predominate in the 1978 landings.

Some preliminary results of an oceanographic investigation in the Kuroshio Extension fishing grounds by the RV Shoyo Maru were reported in a paper by Morita (WP-4). In May and June 1978, oceanographic conditions were measured in conjunction with pole-and-line fishing and albacore tagging east of long. 155°E. Profiles of temperature and other parameters were charted. Analysis of these data will help further the understanding of the complex relationships between fishing conditions and oceanographic processes.

In another working paper, Laurs (WP-7) reported early results of experiments using tetracycline-injected albacore to study "daily" ring formation in albacore otoliths. The study's objective is to determine whether the fine rings are actually formed on a daily basis as many age-and-growth investigations now assume. During 1977 and 1978 nearly 1,800 albacore were caught by chartered U.S. bait boats in the eastern North Pacific, then dart-tagged, injected with 150 mg of oxytetracycline and released. Seventeen otoliths from 45 recovered fish have been analyzed so far. Tentative results are that 1) there is considerable variation in the time required for a single ring to

be formed, 2) no more than one ring is formed per day, and 3) in most cases more than 1 day is required for each ring added. The study suggests the possibility of some positive bias in growth rate estimates determined with the otolith "daily-increment" procedure.

IV. Stock Evaluation

A. Estimates of Maximum Sustainable Yield (MSY)

Estimates of MSY for the North Pacific albacore resource were reviewed. Two methods have been employed to estimate MSY: 1) the generalized production model [used by Shiohama and Morita in 1975 and by Shiohama (WP-1) in this workshop], and 2) a model linking stock-recruitment relationships and yield-per-recruit functions [used by Wetherall and Yong in 1975]. When the Schaefer form of the production model is considered, results from the two approaches have been similar and MSY has been estimated to be between 100,000 and 120,000 MT (Table 4).

As a result of the special partitioning he used and the differences in time periods considered, the normalized CPUE statistics reported by Shiohama in WP-1 are somewhat different from those given here in Table 3; nor are his total catch figures quite the same as those listed in Table 1. Because Tables 1 and 3 give the most up-to-date statistics, a series of production models were fitted to these data following the 1978 workshop. When the Schaefer version was used and data from 1965 to 1976 were analyzed, MSY was estimated to be 207,000 MT, compared to Shiohama's corresponding estimate of 113,000 MT (Table 4). These MSY's would be achieved at effort levels 180% and 27% higher than the 1976 level, respectively. When data covering the entire 1961-76 period were treated, the Schaefer model estimate of MSY was 170,000 MT at an effort level 120% greater than in 1976. Even higher estimates were obtained when non-Schaefer forms of the model were examined.

One difficulty with these production model estimates is that in each case there is relatively little variation in CPUE and effort, and data are not available from the region of the right hand or "descending" limb of the curve, i.e., the region of overfishing (Figure 3). As a result, the MSY parameters are estimated with very low precision. For example, approximate 95% confidence limits on MSY were estimated to be [55,000 MT, 171,000 MT] using Shiohama's data and the Schaefer model, and [0 MT, 648,000 MT] and [0 MT, 509,000 MT] for the two cases above employing updated statistics. One can have no confidence in MSY estimates falling so far outside the range of observed catches.

The foregoing discussion assumes that the fundamental assumptions of the production model are satisfied. If so, then the problems of estimating MSY with reasonable precision are basically statistical. While some of the current estimates of MSY and optimum effort amount to projections beyond the limits of experienced catch and effort and are therefore highly imprecise, precision should increase as more data are added and as the ranges of catch and effort expand. In the meantime the Schaefer model regressions indicate that average stock size, as indexed by CPUE, has not been significantly reduced by the effort exerted to date.

However, even if such improved statistics become available standard production model analyses may not give very useful results, since several kinds of systematic bias may exist. Among these are 1) the production model analysis assumes a single, homogeneous group of fish with uniform rates of biomass production and fishing mortality, whereas in fact both productivity and fishing mortality are age-specific. The average productivity and yield potential of the stock therefore depend heavily on age-structure and the age-specificity of fishing mortality. The albacore resource is composed of several year-classes, and the three major fisheries harvest different (but overlapping) segments of the exploitable population; 2) the analyses so far have assumed a single North Pacific albacore stock, whereas a more complicated stock structure, involving at least two stocks, has been hypothesized on the basis of extensive tagging studies; 3) for reasons elaborated above, changes in CPUE may not faithfully reflect real changes in stock size.

If these conditions exist then the MSY estimates computed using the standard production model are meaningless and other methods must be developed to estimate the average annual yield potential and to provide reliable guidance for judging the status of the stock. Since year-to-year variations in recruitment and availability are high, more sophisticated, dynamic assessment measures will be needed for effective analysis of fishing policies.

B. Condition of Stock

The abrupt decline in the catch and CPUE of North Pacific albacore in 1977 in the United States and Japanese surface fisheries has focused attention on the need for careful monitoring of the stock and an evaluation of fishing strategy and practices. The conclusion of workshop participants was that environmental conditions--particularly the abnormally weak development of frontal structure in the principal fishing grounds--were probably the chief cause of a sudden drop in availability and/or catchability, and hence a reduction in catch and catch rates. A second possibility is that recruitment, known to undergo fairly wide natural variation, was relatively low during the 1975-77 period. A full evaluation of this hypothesis

would require careful examination of unbiased age-specific abundance indices. Such measures have not yet been constructed. In these two particular explanations, fishing effort itself is not regarded as a principal cause of the reduction in catch and catch rates; availability is presumably dictated by environmental conditions and recruitment fluctuations are seen as independent of spawning stock size.

However, serious questions about overfishing cannot be neglected. Here we distinguish between two types of overfishing: 1) In growth overfishing recruitment is not affected by fishing at the prevailing levels of effort, but the average size of harvested fish is below the optimum size from the standpoint of maximizing yield per recruit. Studies have shown that this type of overfishing is characteristic of the North Pacific albacore harvest; given the present constraints and configuration of the surface fisheries, maximization of yield per recruit is probably not feasible. However, the concentration of the Japanese pole-and-line fleet on increasingly smaller albacore in the northern reaches of the Frontal Zone is clearly worsening the growth overfishing situation. 2) The more serious type of overfishing is recruitment overfishing, which results when fishing mortality reduces spawning stock to levels so low that recruitment is impaired. Is it possible that the rapid growth in the aggregate albacore catch (as experienced prior to 1977), coupled with the downward shift in size selectivity, is eroding the reproductive capacity of the albacore stock? To help answer this question, reliable methods must be developed to monitor both recruitment and reproductive capacity. In the meantime, while most production model analyses indicate that fishing effort is still less than the level producing MSY, this evaluation should be viewed circumspectly. Further, for reasons discussed above, the validity of the standard production model as a guide to management analysis for North Pacific albacore must be investigated critically.

V. Recommendations for Further Research

A. Highest Priority Research Task

The research most urgently needed is a thorough evaluation of stock assessment techniques. This work should include 1) analysis of the assumptions, data requirements, robustness, limitations, effectiveness, and appropriateness of the standard methods now in use, and 2) a plan for surmounting the shortcomings of present techniques and for assuring that the critical needs of stock monitoring and fishery evaluation are fully met. This task should be given the highest priority.

B. Other Research Needs

In addition to this major research requirement, there are several other areas needing special attention and emphasis. Specifically,

1) The U.S. system of vessel logbooks, fishermen interviews, and port sampling for size composition must be continued and funded at effective levels. The system should be evaluated from the standpoint of statistical design so that it is as efficient and effective as possible given the basic needs of stock assessment and fishery analysis. [This evaluation would logically be done after or in conjunction with V. A. above.] The U.S. sampling effort should be extended to cover the bait boat fleet.

2) In the Japanese pole-and-line fishery improvements are needed in the measurement of fishing effort. Actual days of fishing should be recorded rather than just days of successful fishing and other measures of effort, such as the number of pole-days of fishing, should be considered.

3) In the Canadian fishery, the collection of logbooks data from albacore trollers should be strengthened.

4) Statistics on the operation of the longliners and bait boats from Taiwan and the Republic of Korea should be obtained and added in future analyses of the albacore resource.

5) The historical size- and age-composition of the albacore catch should be determined using the best available data and the best procedures for assigning age and for combining data from different fisheries, areas, and time periods.

6) The fishing power coefficients for U.S. jig vessels should be re-estimated taking into consideration new information on the use of navigational equipment and other fishing aids.

7) The relationships between fish availability, fishing success, and oceanographic conditions, such as frontal structure development, should be studied further, and taken into consideration in evaluations of stock conditions.

8) Studies on albacore migration and stock identity should be continued and alternative stock structure hypotheses should be considered in future stock assessments.

9) Indices of recruitment and spawning biomass or population fecundity should be developed and monitored as a regular part of stock appraisal.

10) Comprehensive descriptive profiles should be developed for each fishery, preferably within the next year. These should include descriptions of such characteristics as fishing effort, type and number of vessels, species composition of catch, gear, and vessel parameters, fishing techniques and tactics, historical changes in technology, and estimates of catch capacity and new vessel construction.

VI. Arrangements for Next Workshop

The Fourth North Pacific Albacore Workshop will be hosted by the Far Seas Fisheries Research Laboratory in Shimizu, Japan. Dates for the meeting and other details will be worked out through correspondence between scientists of the Far Seas Laboratory and the Southwest Fisheries Center's Laboratory in La Jolla, California.

Table 1.--Catches of North Pacific albacore in metric tons, 1961-77.
(dashes indicate no estimate available)

Year	Japan[1]				United States[2]			Canada	Total[3]
	Pole-and-line	Longline	Other gears	Total	Pole-and-line	Jig	Total	Jig	
1961	18,636	15,999	--	34,635	2,837	12,054	14,891	4	49,530
1962	8,729	12,617	--	21,346	1,085	19,753	20,838	1	42,185
1963	26,420	11,445	--	37,865	2,432	25,142	27,574	5	65,444
1964	23,858	11,558	--	35,416	3,411	18,389	21,800	3	57,219
1965	41,491	11,214	121	52,826	417	16,461	16,878	15	69,719
1966	22,830	20,874	585	44,289	1,600	15,169	16,769	44	61,102
1967	30,481	24,374	520	55,375	4,113	17,814	21,927	161	77,463
1968	16,597	19,040	1,109	36,746	4,906	20,441	25,347	1,028	63,121
1969	31,912	18,006	1,480	51,398	2,996	18,826	21,822	1,365	74,585
1970	24,263	15,372	956	40,591	4,416	21,039	25,455	354	66,400
1971	52,957	10,915	1,262	65,134	2,071	22,196	24,267	1,587	90,988
1972	60,591	12,622	922	74,135	3,750	23,600	27,350	3,558	105,043
1973	69,640	16,000	1,922	87,562	2,236	15,652	17,888	1,720	107,170
1974	73,576	12,952	1,289	87,817	4,777	20,177	24,954	1,207	113,978
1975	52,157	9,931	568	62,656	3,243	18,926	22,169	101	84,926
1976	85,336	15,738	2,464	103,538	2,700	16,314	19,014	252	122,804
1977[4]	31,934	10,000	2,500	44,434	1,497	10,012	11,509	53	55,996

[1]Japanese longline catch for 1961-68 excludes minor amount taken by vessels under 20 gross tons. Longline catch in weight is estimated by multiplying annual number of fish caught by an average weight statistic.

[2]United States pole-and-line catch excludes minor amount taken by vessels not submitting logbooks to IATTC; this amount is included in the jig catch.

[3]Omitted are unknown but minor catches by United States sport fishermen and by longline and pole-and-line vessels of the Republic of Korea and Taiwan.

[4]1977 figures are preliminary.

Table 2.--Number of Japanese pole-and-line albacore vessels by size.

Year	Total number	Size of vessel (gross tons)			
		20-50	50-100	100-200	>200
1965	572	298	91	148	35
1966	571	299	71	167	34
1967	564	296	54	173	41
1968	561	276	60	170	55
1969	528	248	71	156	53
1970	512	220	91	140	61
1971	510	165	133	129	83
1972	554	131	162	116	145
1973	582	93	210	80	199
1974	716	136	255	98	227
1975	696	95	277	45	279
1976	653	51	318	17	267

Table 3.--Actual and normalized CPUE statistics for major North Pacific albacore fisheries, 1961-77.

Year	Actual CPUE[1]					Normalized CPUE[2]				
	Japan pole-and-line	United States jig	Japan longline[3]			Japan pole-and-line	United States jig	Japan longline[3]		
			"Young" area	"Adult" area	Entire area			"Young" area	"Adult" area	Entire area
1961	4.40	69.17	0.55	0.14	0.25	0.72	0.68	0.77	0.58	0.76
1962	7.22	124.59	0.67	0.14	0.30	1.18	1.23	0.94	0.58	0.91
1963	6.29	132.09	0.68	0.19	0.32	1.03	1.30	0.96	0.78	0.97
1964	6.86	97.61	0.90	0.19	0.40	1.12	0.96	1.27	0.78	1.21
1965	6.26	89.07	0.70	0.25	0.33	1.02	0.88	0.99	1.03	1.00
1966	5.94	90.45	1.20	0.27	0.54	0.97	0.89	1.69	1.11	1.64
1967	6.09	126.83	0.88	0.29	0.40	0.99	1.25	1.24	1.20	1.21
1968	5.34	135.23	0.84	0.29	0.38	0.87	1.34	1.18	1.20	1.15
1969	4.95	112.57	0.60	0.31	0.28	0.81	1.11	0.84	1.28	0.85
1970	6.13	127.39	0.66	0.27	0.31	1.00	1.26	0.93	1.11	0.94
1971	6.94	96.68	0.43	0.22	0.21	1.13	0.96	0.61	0.91	0.64
1972	6.25	61.08	0.63	0.30	0.30	1.02	0.60	0.89	1.24	0.91
1973	5.49	82.89	0.85	0.30	0.38	0.90	0.82	1.20	1.24	1.15
1974	7.81	105.17	0.64	0.30	0.34	1.27	1.04	0.90	1.24	1.03
1975	5.95	99.81	0.46	0.21	0.23	0.97	0.98	0.65	0.86	0.70
1976	6.13	69.22	0.66	0.21	0.30	1.00	0.68	0.93	0.86	0.91
1977	2.49	59.90	--	--	--	--	--	--	--	--
Mean 1961-76	6.13	101.24	0.71	0.24	0.33					

[1]Units: MT/vessel-day for Japan pole-and-line; fish/vessel-day for United States jig; fish/100 hooks for Japan longline.

[2]Actual CPUE divided by 1961-76 mean.

[3]"Young" area is 25°-45°N from October to March and 30°-45°N from April to September. "Adult" area is 0°-25°N. Entire area is 0°-45°N.

Table 4.--Estimates of maximum sustainable yield (MSY) for North Pacific albacore.

Case	Type of model	Years	Data points	$\hat{MSY}$ (10^3 MT)	95% confidence limits on MSY		$\left(\frac{F_{\hat{opt}}}{F_{1976}}\right)$	Source of data/estimates
					Lower	Upper		
1	Production model, 4-yr smoothing, m = 2 (fixed)	1965-76	9	113	55	171	1.27	Shiohama (WP-1, Table 3, case 1)[1]
2	Production model, 4-yr smoothing, m = 1.01 (variable)	1965-76	9	130	--	--	1.89	Shiohama (WP-1, Table 3, case 1)[1]
3	Production model, 4-yr smoothing, m = 2 (fixed)	1965-76	9	207	0	648	2.80	This report, Tables 1 and 2[2]
4	Production model, 4-yr smoothing, m = 0 (variable)	1965-76	9	638	--	--	--	This report, Tables 1 and 2[2]
5	Production model, 4-yr smoothing, m = 2 (fixed)	1961-76	13	170	0	509	2.20	This report, Tables 1 and 2
6	Production model, 4-yr smoothing, m = 0.99 (variable)	1961-76	13	224	--	--	3.90	This report, Tables 1 and 2
7	Production model, 4-yr smoothing, m = 2 (fixed)	1961-73	10	115	--	--	--	Shiohama and Morita, 1975 workshop
8	Yield per recruit/ spawner-recruit	1952-72	--	116	--	--	--	Wetherall and Yong, 1975 workshop

[1]The standardized effort for 1965 was corrected to 67,544 from the original value of 65,544.

[2]Normalized CPUE in these cases was computed by dividing actual CPUE by the 1965-76 mean, instead of the 1961-76 mean.

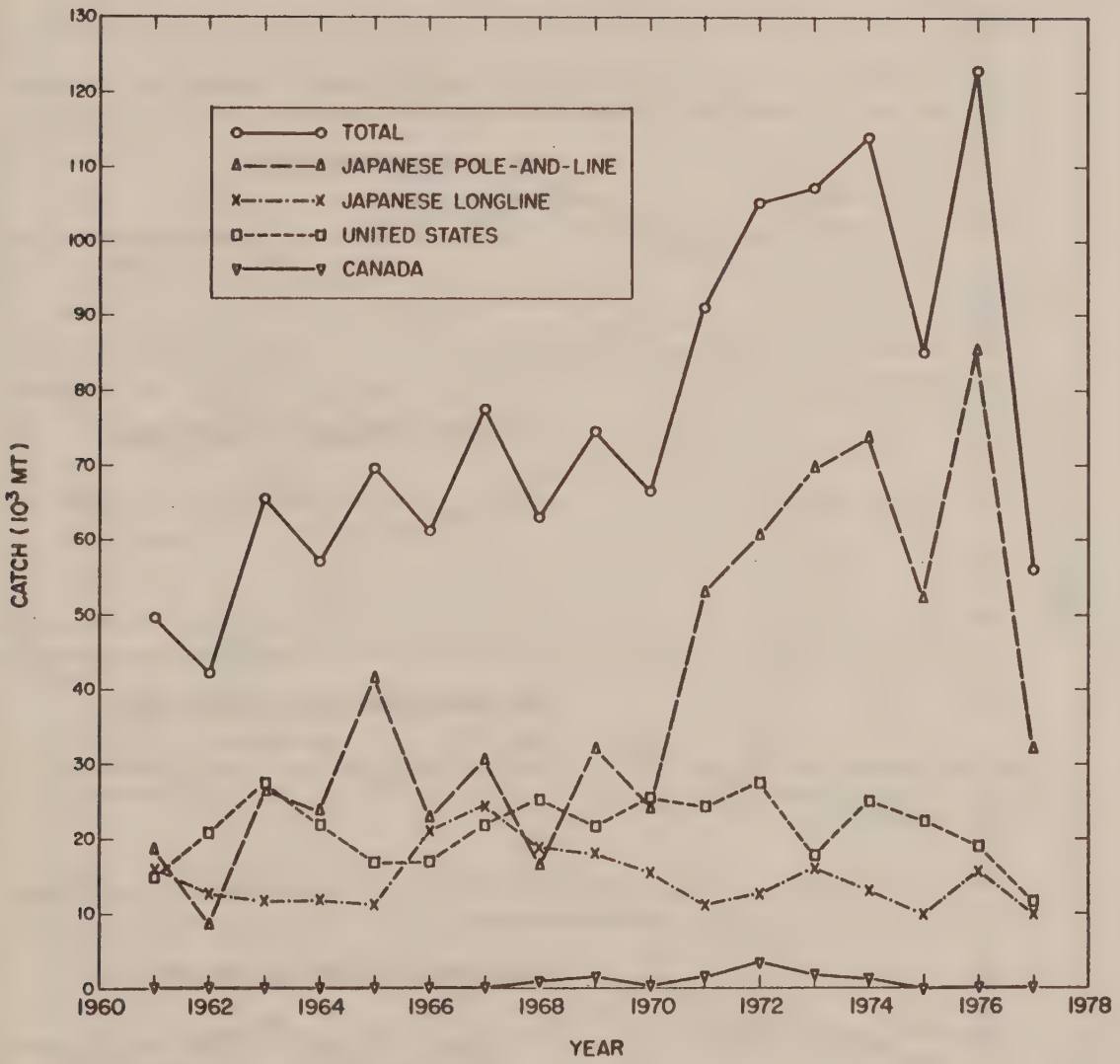

Figure 1.--Estimated annual catch of North Pacific albacore, 1961-77, in 10^3 metric tons. Total catch includes small amount taken in minor fisheries as well as the catch by the indicated major fisheries.

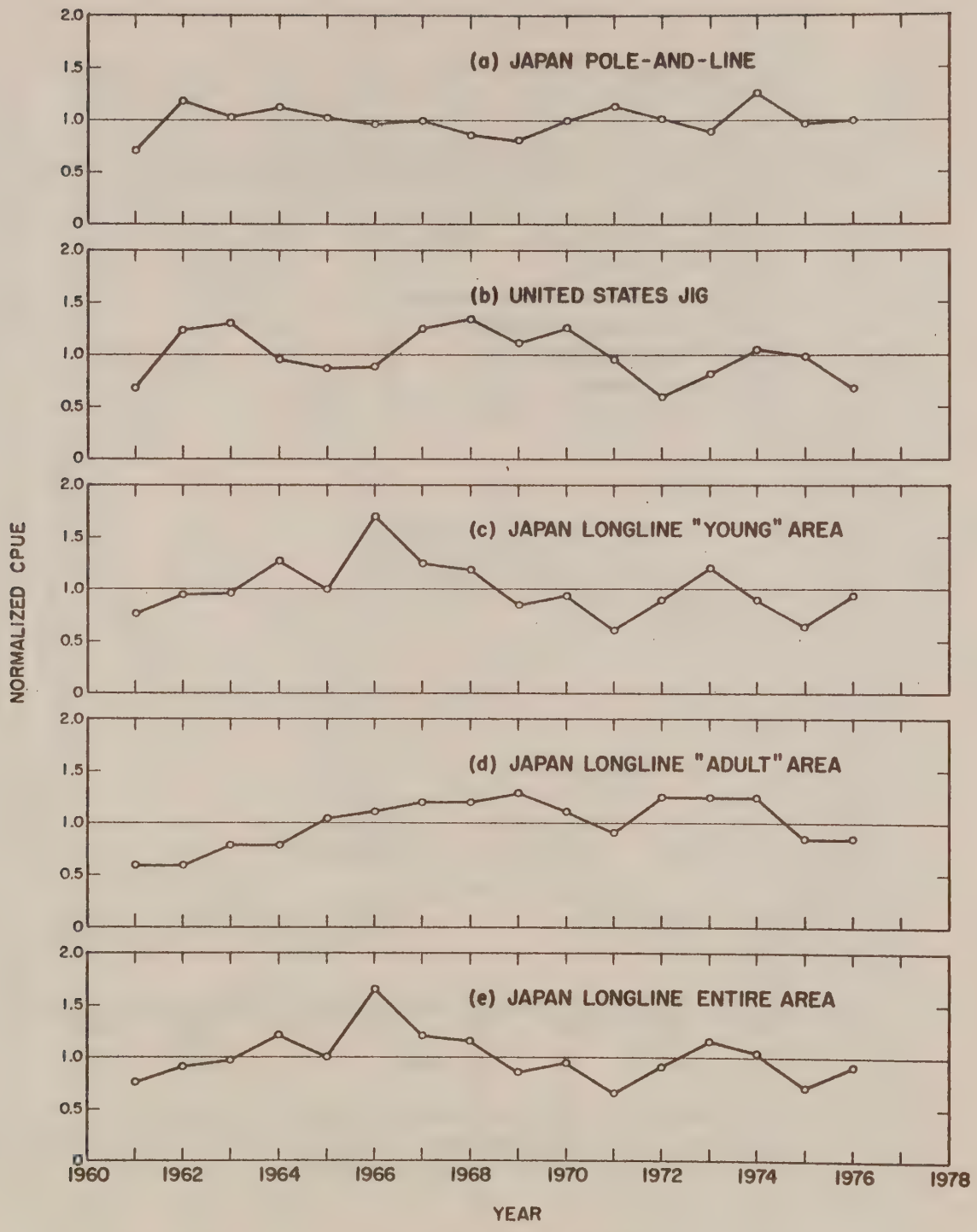

Figure 2.--Normalized catch per unit effort statistics for major North Pacific albacore fisheries, 1961-76.

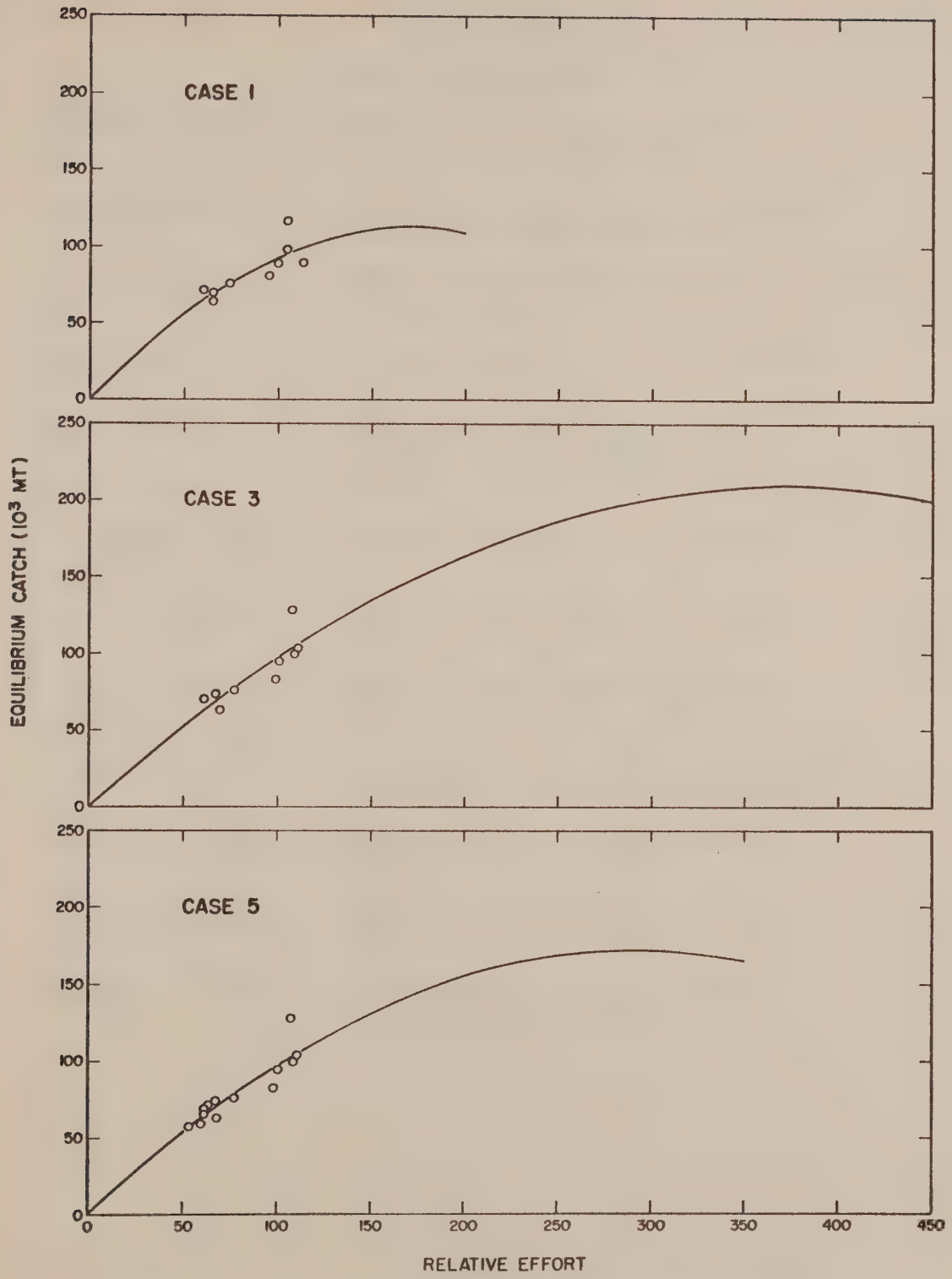

Figure 3.--Three production models for North Pacific albacore. Cases are described in Table 4.

Appendix A

LIST OF PARTICIPANTS

Norman Bartoo	National Marine Fisheries Service, La Jolla, California, U.S.A.
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Appendix B

AGENDA AND SCHEDULE

September 13 - 0900-1200

1. Introductory remarks, selection of workshop chairman and rapporteurs

2. Adoption of workshop agenda and schedule

3. Review of North Pacific albacore fisheries, 1977-78

   - Japan report
   - United States report
   - Canada report
   - Exchange and distribution of data on catch, fishing effort, catch size composition, vessel statistics, etc.
   - Completion and updating of basic fishery data tables

September 13 - 1300-1700

4. Presentation and discussion of working papers

   a. NPALB/78/WP-1 Stock assessment of North Pacific albacore by production model analysis (T. Shiohama)

   b. NPALB/78/WP-2 The present situation of the prediction of summer albacore pole-and-line fishery in the northwestern Pacific (T. Shiohama)

   c. NPALB/78/WP-5 Use of age-specific abundance indices and effective effort statistics to assess the North Pacific albacore stock - Preliminary results (J. Wetherall and M. Yong)

   d. NPALB/78/WP-3 Considerations on the fishing conditions in the surface albacore fishery in 1977 and 1978 (S. Kikawa)

   e. NPALB/78/WP-6 Some factors affecting the 1977 U.S. albacore fishery (R. M. Laurs)

   f. NPALB/78/WP-4 The results of the oceanographic observations by the R/V Shoyo Maru in the fishing ground in the Kuroshio Extension area (J. Morita)

g. NPALB/78/WP-7 Albacore otolith/tetracycline study to evaluate otolith daily ring increment method for growth determination - progress report (R. M. Laurs)

September 14 - 0900-1100

5. Evaluation of findings and drafting of summary statement on status of stock, fishing conditions, etc.

6. Discussion of research needs and recommendations

September 14 - 1400-1600

7. Adoption of draft workshop report

8. Plans for next meeting

9. Adjournment

Appendix C

LIST OF DOCUMENTS

Data

NPALB/78/D-1 - Catches of North Pacific albacore in metric tons, 1961-1976

NPALB/78/D-2 - Catch per unit of effort (CPUE) of North Pacific albacore by fishery

NPALB/78/D-3 - Number of Japanese pole-and-line albacore vessels by size

NPALB/78/D-4 - Sample length composition of U.S. albacore landings, 1976

NPALB/78/D-5 - Sample length composition of U.S. albacore landings, 1977

NPALB/78/D-6 - U.S. albacore landings in pounds by year, month, and state

NPALB/78/D-7 - Annual estimates of catch, effort, fishing intensity and CPUE of albacore caught by longline vessels (over 20 tons in size), 1952-1976 (T. Shiohama)

NPALB/78/D-8 - Catches of North Pacific albacore in metric tons, 1969-1976

NPALB/78/D-9 - Japanese albacore landings by various fishing methods, 1969-1976

NPALB/78/D-10 - Japanese pole-and-line length-frequency data, 1974-1976

NPALB/78/D-11 - Japanese longline length-frequency data, 1974-1976

Working Papers

NPALB/78/WP-1 - Stock assessment of North Pacific albacore by production model analysis (T. Shiohama)

NPALB/78/WP-2 - The present situation of the prediction of summer albacore pole-and-line fishery in the northwestern Pacific (T. Shiohama)

NPALB/78/WP-3 - Considerations on the fishing conditions in the surface albacore fishery in 1977 and 1978 (S. Kikawa)

NPALB/78/WP-4 - The results of the oceanographic observations by the R/V Shoyo Maru in the fishing ground in the Kuroshio Extension area (J. Morita)

NPALB/78/WP-5 - Use of age-specific abundance indices and effective effort statistics to assess the North Pacific albacore stock - Preliminary results (J. Wetherall and M. Yong)

NPALB/78/WP-6 - Some factors affecting the 1977 U.S. albacore fishery (R. M. Laurs)

NPALB/78/WP-7 - Albacore otolith/tetracycline study to evaluate otolith daily ring increment method for growth determination - progress report (R. M. Laurs)

FISHERIES INFORMATION FOR

WESTERN SAMOA AND THE KINGDOM OF TONGA

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November 1978

WESTERN SAMOA

In Western Samoa, fishing is basically a subsistence activity, although some commercial fishing occurs; there is no organized fish market through which the fish are sold. Fishing is concentrated primarily on the fringing reefs and lagoons. The Western Samoan fishermen catch any edible organisms, irrespective of size, including fish, shells, crustaceans, turtles, bêche-de-mer, squids, octopus, and sea urchins as well as large quantities of "palolo," the wormlike sacs of eggs and sperm of a sea annelid (Eunice viridis) when in season. In use are 1,500 canoes and 50 catamarans, all powered with outboard motors.

To capture their prey, the fishermen use fixed fish traps, gill net, beach seine, stake net, eel trap, spear, pole-and-line, trolling line, handline, and cast net. There are about 400 full-time and 7,000 part-time fishermen using mainly spear and net to harvest organisms from the reef area. The result is that there is considerable fishing pressure exerted and the reef and lagoon fauna are undoubtedly overfished. Fortunately, schools of bigeye scad enter the lagoons occasionally, thus relieving some of the pressure on the reef stock.

Trolling for tuna is another of the principal methods of fishing. Using motorized double-hull canoes and fishing outside the reef, about 400 Western Samoan fishermen find trolling one of the most economical ways to fish because of the low initial investment in gear, simplicity of the technique, and the recreational value involved. Despite the seasonally good catches made by these trollers, there are periods when the availability of tuna is either low or tuna are entirely absent from Western Samoan waters. Therefore, to insure profitability of these trollers, bottom handline fishing along the outer reef was begun in 1975.

Good bottom fishing grounds are usually located at the drop-off of the outer reef at depths between 100 and 150 m. Because currents around the islands are generally swift, the boats anchor on the grounds. The major species caught by handlining in Western Samoa include shark, sharptooth snapper (Pristipomoides typus), rosy job rish (Aprion microlepus), Malabar red snapper (Lutjanus malabaricus), longface emperor (Lethrinidae), castor-oil fish (Ruvettus pretiosus), red snapper (Lutjanus bohar), grouper (Serranidae), green job fish (Aprion virescens), snake mackerel (Promethichthys prometheus), and small-toothed job fish (Aphareus furcatus).

The small domestic catch of Western Samoa is either consumed directly by the fishermen and their dependents or sold locally. The demand for fish far exceeds the domestically

caught supply; therefore, very considerable imports of mostly canned pilchard from South Africa and small amounts of frozen New Zealand fish are necessary.

There is an almost total lack of marketing infrastructure and the result is that very little fresh fish reach Apia, the chief town and population center. Furthermore, there is a serious shortage of scientific and technical skills in every sector of the fishing industry and the effect has been to restrict rapid development of the local fisheries. Attempts to develop fishing village associations by the Fisheries Division have not succeeded, but family ownership of outboard motors and boats have shown a steady increase.

In 1965-76, the domestic catch of marine fish and shellfish changed very little, varying between 900 and 1,100 MT and averaging 925 MT.

The potential for increasing local fish production lies in developing a fishery for skipjack tuna, sizeable schools of which have been sighted near Western Samoa. UNDP/FAO presently has a project to develop such a fishery; however, baitfish is very scarce. In 1970-72, for example, bait surveys conducted by National Marine Fisheries Service in the bays and harbors of Western Samoa showed very small quantities of baitfish, primarily silverside (Pranesus pinguis), in Apia Harbor. Because scarcity of bait has handicapped development of the skipjack fishery, Western Samoa has embarked on a program of culturing mollies or topminnows (Poeciliidae) to be used as bait, similar to a large-scale experiment presently being carried on in American Samoa.

Another area which offers considerable potential for further development is the deep-water handline fishery for snappers, groupers and other demersal fishes, because Western Samoa is blessed with extensive shelf areas. But local crafts needed to be upgraded to give them the capability to fish outside the reef and the local fishermen needed training in new techniques, boatbuilding, engine operation, and maintenance.

In a step to provide such assistance, UNDP/FAO has acquired the services of a master fisherman and a fishery advisor to train the local citizens in various fishing techniques. A demonstration team of two boats with outboard motors and each manned by two fishermen taught fishing techniques in Western Samoa for an 11-month period. The results demonstrated that an 8.5-m boat operated by an experienced crew can catch up to 10 MT of bottom fish in about 115 trips per year. Furthermore, two types of fishing crafts have been tested and were found to be sufficiently seaworthy to remain at sea for night fishing

and also provide reasonable comfort in the choppy waters often encountered around Western Samoa. One was a catamaran-type boat, a modified version of the local double-hulled canoe but built of pressure-treated marine plywood. The other was an 8.5-m, 20-hp, diesel-powered boat averaging speeds of 9 knots.

In Western Samoa, ciguatera poisoning is not a serious problem. The red snapper, L. bohar, which is the only species thus far implicated in poisoning cases, constitutes only 5% of the total catch.

TONGA

Tonga has no organized fishing industry in a strictly commercial sense. The industry lacks professional fishermen and is at a very early stage of development, based mainly on the inshore and nearshore fish resources. There are between 1,300 and 1,400 residents engaged in fisheries in the southern and central islands and an additional 300 in the northern islands. Among the 500 small crafts in use are outrigger canoes, skiffs with outboard motors, launches with inboard engine, and sailing boats.

The fishing gear used are the traditional types including spear, gill net, trammel net, beach seine, cast net, coconut frond net, turtle net, handline, and pole-and-line. The main fisheries include tuna longlining, reef and inshore handlining (commonly used at night with light attraction), surface trolling and trapping.

Longline fishing for tuna and miscellaneous pelagic species within Tongan waters began in 1970 and continues to show relatively good progress, although the present operation is not self-sustaining. The Fisheries Division of the Department of Agriculture operates the 112-GRT vessel, which is crewed by Tongans. A second longliner, donated to Tonga by the Japanese Government, recently went into service with an all-Tongan crew.

Concerning the development of a skipjack fishing industry, feasibility studies conducted by the Japanese and subsequently by UNDP/FAO showed that among the 200-300 islets scattered throughout the Tongan Archipelago, waters around the northern islets seem most promising as baiting sites. Although stocks of baitfish appear to be insufficient to support full-scale development of a skipjack fishery, fishing trials and reports from fishermen indicate that surface tuna schools occur in sufficient numbers in October-March to justify the development of a small operation for the local market.

In baiting operations, initial trials with the Japanese fixed trap net (teichi-ami) have proven highly successful in catching bait. One trap, fishing continuously at Pangaimotu near Tongatapu, produced 6.5 MT of several species of fish including big-eyed scad (Trachurops crumenophthalmus), spotted herring (Harengula ovalis), round herring (Dussumiera sp.) and mackerel scad (Decapterus sp.). Of these, 53.2% were of suitable size as live bait for skipjack tuna fishing, whereas the larger fish had a ready market among the local residents.

The inshore lagoon and near reef catches consist of a wide assortment of tropical species including jack crevally

(Carangidae), flyingfish (Exocoetidae), Spanish mackerel (Scombridae), barracuda (Sphyraenidae), parrotfish (Scaridae), snapper (Lutjanidae), goatfish (Mullidae), and milkfish (Chanidae). Most fish marketed are small or juveniles of large species, usually 15 to 25 cm in length. Among the main species marketed throughout the year are juvenile emperor (Lethrinus variegatus), rabbitfish (Siganus oramin), and big-eyed scad. Other commonly marketed fishes include unicorn-fish (Naso unicornis), blue-line snapper (Lutjanus kasmira), triggerfishes (Balistidae), wrasses (Labridae), longtoms (Belonidae), porcupinefish (Diodontidae), stonefishes (Scorpaenidae), and mullet (Mugil cephalus).

Among various other marine animals harvested for consumption are holothurians (bêche-de-mer) of which only the intestines are marketed, large, short-spined sea urchins, which are very popular, and octopus, which are either sold fresh or dried and smoked. Until recently, small quantities of spiny lobsters were also caught and exported, but the company involved has switched to the more profitable inter-island freight business.

In Tonga, the entire catch is consumed domestically. The longline catch, with the exception of a few tons which are sold in Pago Pago during dry-docking or repair stop-overs, is sold in Nuku'alofa by the Government Marketing Authority, which owns and operates the island's only cold storage and ice-making plant. The remainder of the fish catch is sold directly to the consumer by the fishermen. On the island of Tongatapu, it has been necessary to supplement the demand for fish with imports of canned fish.

Tonga has taken steps to collect fish catch data by introducing a statistical collection system. In 1971-76, the catch of marine fish and shellfish varied from 500 to 1,019 MT and averaged 707 MT. On the other hand, the lack of a marketing infrastructure, poor communication between islands and shortage of trained personnel have all hindered the rapid development of the Tongan fisheries. At the present time, dry-docking and ship-repair facilities can handle only small crafts. To help the struggling fishing industry, the Tongan Government has exempted fishing gear and marine equipment from the 33% import tax.

The prospects for developing fishery resources in the Tonga Islands appear to be extremely good because of the extensive shallow-water areas available to fishermen. The fishing grounds are all within cruising range of 30-40 fishing boats ranging in size from 9 to 12 m. In addition, exploratory

handline fishing has shown good potentials for outer-reef resources composed mainly of snappers and groupers. A start has also been made in aquaculture with the establishment of a small pilot project for oyster growing in 1973 in Funga'uta lagoon. The project, funded by FAO/SPIFDA, is now being supervised by a U.S. Peace Corps volunteer.

In Tonga, ciguatera poisoning does not appear to be a serious problem.

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10/24/78

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D.O.

Hazel

- Fisheries info for Western Samoa and the Kingdom of Tonga

I just noticed in the reading file the above document prepared for Senator Jackson's office via Mickey Vrooman, NMFS, Washington, D.C. This is the kind of information which is extremely useful requiring a lot of searching. So that it will not get lost in the files and buried after a period, may I suggest that it be processed as an admin report where the information can be retrievable? In the present format, one has to remember that it was in the reading file and that it was prepared by Uchida recently. And in our old age and senility, it is becoming more and more difficult to remember these very important details.

Admin # 26 H, 1978

~~To~~

A

bc: RNU

October 13, 1978

To: F52, Mickey Vrooman, NMFS, Washington, DC

From: F142, Richard S. Shomura, Director, Honolulu Laboratory
s/T Otsu for

Subject: Fisheries info for Western Samoa and the Kingdom of Tonga

Enclosed is the requested information covering the fish and fisheries of Western Samoa and Tonga. I hope the reports meet your needs in responding to the request from Senator Jackson's office.

Enclosure (by RNU)

RSShomura:cay

USING MARKOV DECISION MODELS AND RELATED TECHNIQUES FOR PURPOSES OTHER THAN SIMPLE OPTIMIZATION I: ANALYZING THE CONSEQUENCES OF POLICY ALTERNATIVES ON THE MANAGEMENT OF SALMON RUNS

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December 1978

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ABSTRACT

The mathematics of Markov decision processes and related techniques are used to analyze a model relevant to salmon management. It is shown that the choice of grid can have a significant effect on the results obtained. Optimal policies that maximize total expected discounted return are too variable. Smoothing costs are included to tradeoff long-run total return against the smoothness of the year-to-year fluctuations in the allowed harvest. Simpler, approximate policies that have a smoothing effect are also found. Preliminary analysis suggests the results are robust against misspecification of the parameters of the model. Concepts such as MSY (maximum sustainable yield) would seem to impute a very high smoothing cost, and are probably not practical for fish populations with a significant degree of randomness.

INTRODUCTION

The history of most managed natural populations is one of sizable, non-deterministic variations in the dynamics of the population. This observed variation tends to have two sources, the incompleteness or inaccuracy of our understanding or modeling of the population and actual randomness in the system due to causes such as environmental variability. Most of the analyses for managing natural populations assume deterministic behavior, that is the population will behave exactly as the model predicts. Such behavior is implicit in static management regimes such as "optimum sustained yield" and related concepts. It is not difficult to develop realistic scenarios where staying with a supposed sustained yield policy on a varying or stochastic population will produce results far different from that predicted by the deterministic model.

At the same time, advances have been made in the mathematics of stochastic control, particularly in the area of MDPs (Markov decision processes). In this paper, the tools available from MDP's and related techniques are brought to bear on a stochastic model relevant to salmon management. The aim is to use optimization techniques to narrow down the policy choices facing a decisionmaker, and to provide the decisionmaker with as much information as possible. It will be seen that when switching from deterministic to stochastic models, presently held ideas of proper objectives for management do not necessarily carry over intact. Policies that

maximize the expected (discounted) long-term yield often have no allowable harvest a fair percentage of the time, and have large year-to-year fluctuations in the allowable harvest.

As an alternative objective, "smoothing costs" (Mendelssohn 1976) on the fluctuations are added. By parameterizing on the relative value of the smoothing costs, the decisionmaker can be presented with a range of policies that steadily decrease the expected annual harvest, but also decrease the year-to-year fluctuations in the harvest. Policies that approximate optimal "smoothing" policies, but that are easier to implement, are also found.

Finally, uncertainty about the "true" values of the parameters in the model are considered explicitly. Preliminary results suggest that if the class of models being used is correct, then good policies are robust against misspecification of the parameter values. These results suggest that in many real situations, it may not be worth the cost to do extensive research to increase the accuracy of the parameters of the given model; the research, in terms of management, would be justified only if it is leading to new and better models, and not just to supply more accurate parameter estimates.

THE MODEL

The models to be analyzed were developed by Mathews (1967) to describe the spawner-recruit relationships of salmon populations in two rivers that run into Bristol Bay, Alaska. Oceanographic and other factors affect the number of recruits to a degree where the relationships are best modeled by the random equations:

$$\text{Wood River:} \quad x_{t+1} = (e^{d})(4.077y_t)\ \exp\{-0.800y_t\} \qquad (1.1a)$$

$$d \sim N(0,\ 0.2098)$$

$$\text{Branch River:} \quad x_{t+1} = (e^{d})(4.554y_t)\ \exp\{-1.845y_t\} \qquad (1.1b)$$

$$d \sim N(0,\ 0.3352)$$

where y_t is the number of spawners in period t, x_{t+1} is the (random) number of recruits in period t+1, and $d \sim N(a, b)$ denotes that d is a normally distributed random variable, with mean a and variance b.

For deterministic versions of (1.1), the primary objective of management is MSY (maximum sustainable yield), which is equivalent to maximizing the total (discounted) harvest. It has been assumed that the natural extension of this idea is to maximize total expected (discounted) harvest (or if the discount factor is one, the mean per period harvest). More formerly, if E is the expectation operator, and α is a discount factor $0 \leq \alpha < 1$, the problem is to:

$$\text{maximize } E\left\{ \sum_{t=1}^{\infty} \alpha^{t-1} p \cdot (x_t - y_t) \right\} \qquad (1.2)$$

$$\text{subject to } 0 \leq y_t \leq x_t; \text{ and } (1.1)$$

The optimization problem (1.2) can be solved by discretizing the model on a finite grid.

Discretizing the Model

In order to make (1.2) amenable to numerical methods, it is necessary to discretize both the state space and the action space, and then to redefine the transition probabilities etc., on this grid. Several authors (Fox 1973; Bertsekas 1976; Hinderer 1978; Larraneta 1978; Waldmann 1978; Whitt 1978) have suggested techniques to discretize MDP's, and give bounds on the error due to the approximation. We have shown elsewhere (Mendelssohn 1978) that grid choice can have a significant effect on the analysis. An optimal policy and the value of an optimal policy are not greatly affected by the choice of grid, but the estimated probabilistic behavior of the population dynamics is affected significantly by the choice of grid.

A first effort then is to find an adequate grid for the problem, a grid fine enough for both the desired accuracy and for realistic approximations of observed population sizes and coarse enough for computational efficiency. Increased computational efficiency makes it reasonable to solve many variations of a given model, which allows for a more thorough exploration of the management questions of interest and their sensitivity to key assumptions.

Several different grids were tried for (1.2) for both the Branch and Wood Rivers. A discount factor of 0.97 is used, which is roughly equivalent to the value that would arise if the interest rate is assumed to be the difference between the actual interest rate less the rate of inflation. (Many of the computations were performed for discount factors in the range of 0.95-0.99, with little change in the results.)

To discretize (1.2) on a given grid, suppose a grid of k points has been chosen on which to discretize the problem, and assume, as is reasonable for this problem, that the reduced action space (how many spawners to leave) is equivalent to the state space (how many recruits are observed at the beginning of the period). From equations (1.1):

$$P\{x_{t+1} \leq \omega | y_t\} = P\{(e^d)\ R_1 y_t \exp(-R_2 y_t) \leq \omega\}$$
$$= P\{d \leq \ln \omega - \ln a\} \qquad (2.1)$$

where $a = \left(R_1 y_t \exp(-R_2 y_t)\right)$. Let Φ be the standard normal integral for a random variable $\bar{d} = \frac{d}{\sigma}$, and let x_i, x_{i+1} be any two adjacent points on the grid. Then:

$$P\{d \leq \ln x_i - \ln a\} = \Phi\left(\frac{\ln x_i - \ln a}{\sigma}\right)$$

$$P\{d \leq \ln x_{i+1} - \ln a\} = \Phi\left(\frac{\ln x_{i+1} - \ln a}{\sigma}\right)$$

so that one method of discretizing the transistions is:

$$P\{x_{t+1} = x_{i+1} | y_t\} = \Phi\left(\frac{\ln x_{i+1} - \ln a}{\sigma}\right) - \Phi\left(\frac{\ln x_i - \ln a}{\sigma}\right)$$

that is the total probability of going to any state on the interval $(x_i, x_{i+1}]$ when the decision is y_t.

If zero is included as a state, the procedure needs to be modified slightly. Suppose the probability of going to x_1 is known for each decision y. Then an arbitrary fraction of this is assigned as going to the zero state. In this paper, one half of the probability in the interval $[0, x_1]$ is assigned to the zero state. The results have been found not to be sensitive to the value of the fraction.

This procedure is sensible if the zero state is thought of not as absolute zero, but as all states such that the fishery is "absorbed," that is at a low enough population level that it would take years for it to recover and allow fishing again, if it recovers at all. This ad hoc procedure says that some of the probability mass in the interval $[0, x_1]$ actually goes to these states, and that as the interval gets larger, the amount is greater.

A coarser grid implies, in a sense, less information about the state of the system. As the interval $[0, x_1]$ becomes large, our information has decreased about the true state of the population and this increased uncertainty is reflected in increased risk of absorption. Similarly, a finer grid implies more exact information--a grid should not be used which is finer than the precision of the estimate of the population size.

Optimal policies for grids of 16, 26, 51, 101, and 501 equally spaced points (including zero) for both rivers are shown in Table 1. The optimal equilibrium population for the equivalent deterministic models are shown also. All numbers are in units of 10^6 fish.

The optimal policies are all of the base stock variety, that is it is optimal to harvest to a fixed number of spawners, or else not to harvest at all. If the 501-point grid is taken as the standard, it can be seen that each coarser grid has as its base stock size the grid point closest to the base stock size for the 501-point grid.

Figures 1a and 1b give the long-run (ergodic) cumulative distribution of being in any state when following an optimal policy on grids of 16, 26, 51, and 101 points. Grid size can be seen to play a crucial part in estimating the probabilistic behavior of the population. For the Wood River, extinction with probability one is predicted on grids of 16 and 26 points, while the probability is zero on grids of 51 and 101 points, so long as zero is not the initial state. Similar results are valid for the Branch River.

Probability one of extinction occurs because for a finite state Markov chain with an absorbing state, where all states communicate, absorption occurs with probability one; however, the time till absorption and the distribution of population size in intermediate periods can vary greatly. For example, starting with an initial distribution of zero probability of being in the absorbing state, and an equal probability of being in any other state, for the Branch

River a 16-point grid predicts absorption with probability one after 2,000 iterations, the 26-point grid predicts only a 76% chance of absorption after 2,000 iterations, and the 51-point grid predicts only 17% chance of absorption.

When maximizing total expected discounted return, the discounted mean return depends on the values of these intermediate probability distributions, so that coarser grids can be expected to underestimate the long-run value of the harvest.

Finally, for the Wood River, note that the 51- and 101-point grids have similar long-run behavior. These results suggest that in order to find good policies, it is only necessary to use a grid size of 26 to 51 points for the problems under consideration. However, to analyze the long-run (probabilistic) behavior of a given policy, it is necessary to use a grid containing no fewer than 100 points.

It should be reemphasized that the reason for considering a coarser grid is that a smaller problem size allows for many problems to be solved at a small cost. This is desirable to obtain insight into the sensitivity of the problem. However, it is possible to solve quite large problems, making use of a variety of methods to accelerate computations (see for example Porteus 1971; Hastings and van Nunen 1977). For example, the 501-point grid for the Branch River used 1.80 sec of CPU (central processing unit) time to perform the optimization. Computations, when smoothing costs

are included (section 3), have 2,601 states. These used about 5 to 6 min of CPU time to perform the computations, but at a cost of about $20. Our experience is that it is possible to obtain reasonable estimates using coarse grids, and that this suffices for initial policy investigation. However, it is worthwhile to reanalyze the final two or three problems of greatest interest on a finer grid.

POLICY ANALYSIS

For the Wood River, the optimal policy for (1.2) is given by

$$y_t = \text{minimum } (0.770, x_t)$$

and it produces a mean per period harvest of 1.14758, a variance in the harvest of 0.8034, and a standard deviation in the harvest of 0.8963: The median harvest is 0.91, and no harvest occurs roughly 4.3% of the time. A harvest of 25% or less of the mean harvest occurs roughly 15% of the time, while a harvest greater than the mean harvest occurs approximately 38% of the time.

Similarly, for the Branch River, an optimal policy for (1.2) is given by

$$y_t = \text{minimum } \{0.300, x_t\}$$

and it produces a mean per period harvest of 0.6622, a variance in the per period harvest of 0.3745, and a standard deviation of 0.6120. The median harvest is roughly 0.500, there is a 3.9% chance of no

harvest. A harvest of 25% of the mean harvest or less occurs roughly 14.5% of the time, and a harvest greater than the mean harvest occurs approximately 61% of the time.

While these policies are similar in form to policies that are optimal for a deterministic version of (1.2), they differ greatly in the year-to-year dynamics. There are two ways of finding the optimal deterministic policy. The first way is to assume a model of the form:

$$x_{t+1} = R_1 y_t \exp\{-R_2 y_t\} .$$

The second method is to assume a model of the form:

$$x_{t+1} = E(e^d) R_1 y_t \exp\{-R_2 y_t\}$$

The second method is preferable, since it uses all the information available. As d is a normal random variable with mean zero and variance σ^2, it is easy to show that e^d is a lognormal random variable with expectation $\exp\{\frac{1}{2}\sigma^2\}$. Solving for the optimum sustained yield population size for each river gives:

	Wood River	Branch River
x_{OSY}	0.735	0.345
OSY	1.11346	0.63804

Both OSY values are lower than the mean per period harvests in the stochastic models, but the variation is too high to allow this amount to be harvested each year. However, the x_{OSY} level is a good estimate of the base stock size, and it is known a priori from Mendelssohn and Sobel (1979) that a base stock policy is optimal.

In the deterministic model, once x_{OSY} is reached, both the population size and the harvest size are maintained at steady, equilibrium levels. An optimal policy for the stochastic model, however, produces large fluctuations in both, and may allow no harvesting 1 year out of 25 in the long run. For many fisheries, these "boom and bust" conditions may not be acceptable. Many people, especially those with interest or mortgage payments, as are many fishermen, are concerned about smoothness of income received as well as the total amount received.

There are several methods available to try to find a balance between the smoothness of the random income stream and its total discounted dollar value. One method is to include "smoothing costs" into the one-period return. This approach has been studied analytically by Mendelssohn (1976). Let γ be the cost of a unit decrease in the harvest from year to year, and let ε be the cost of a unit increase in the harvest.

If z was harvested last year, then net revenues this year, for any harvest z_t, are decreased by

$$\begin{cases} \gamma \cdot (z - z_t) & \text{if } z > z_t \\ 0 & z = z_t \\ \varepsilon \cdot (z_t - z) & z < z_t \end{cases}$$

Amended to (1.2), this would imply a one-period net benefit of

$$p \cdot (x_t - y_t) - \gamma \cdot \left(z - (x_t - y_t)\right)^+ - \varepsilon \cdot \left((x_t - y_t) - z_t\right)^+$$

where $(a)^+$ denotes the positive part of a. An alternate form is to let $e = \frac{\gamma - \varepsilon}{2}$ and $c = \frac{\gamma + \varepsilon}{2}$. Then the one-period return is:

$$p \cdot (x_t - y_t) + e \cdot (x_t - y_t) - c \cdot |(x_t - y_t) - z_t| - e \cdot z$$

The advantage to the smoothing cost approach is that p, e, and c act the part of relative prices. That is, the relative values of p, e, and c can be interpretated as the relative value of one unit of total income to the relative value of having the between period harvest "smoothed" by one unit. Actual relative values are often difficult to determine. But by parameterizing on e and c, it is possible to present a decisionmaker not only a range of possible "optimal" policies and their consequences, but also some feeling for the relative tradeoff between total income and the smoothness of the received income stream.

For the Wood and Branch Rivers, two sets of computations were performed. The first set assumes that $\gamma = \varepsilon$, that is there is an equal concern for increases in allowable harvest as well as for decreases. This is equivalent to $e = 0.0$, and $c = \gamma$ (or equivalently ε). The motivation for this cost structure is that fishermen typically resist any decrease in the allowed harvest, hence $\gamma > 0$. However, allowing increases in the harvest size often signals fishermen to gear up and invest in equipment, thereby making it even more difficult to decrease the allowable harvest later on. Therefore this cost should be equal to a cost due to a decrease in the harvest.

As a counterbalance to this, a second set of computations were performed with $\gamma > 0$ but $\varepsilon = 0$, that is a cost only if the harvest is decreased. This is equivalent to $c = e = \frac{\gamma}{2}$.

For the first set of computations, with $e = 0.0$, values of c of 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, and 2.00 were used. These are equivalent to relative values of $\frac{1}{8}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, $\frac{3}{4}$, $\frac{7}{8}$, and 1. For the second set of runs, with $c = e$, values of 0.25, 0.50, 0.75, 1.00, and 1.25 were used. These are equivalent to a ratio of γ/p equal to $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{4}$. The results are summarized in Figures 2(a)-(m) and Figures 3(a)-(m), which show an optimal policy for each river for each of these cases. All computations were performed on 26 point grids.

The figures are read as follows. Suppose z was harvested last year, and x is the observed population size this period. Find the point (x, z) on the graph, and follow the arrow in that zone to the appropriate boundary as indicated. Then read off the z value of this point, and this is the optimal amount to harvest this period.

For example, if c = 0.50, e = 0.00, x_t = 0.84, and the harvest last period was 0.28, Figure 2(b) says an optimal policy for the Wood River is to harvest 0.28 this period. Note that the dashed line is the equivalent base stock harvest with no smoothing costs.

While the policies in Figures 2 and 3 are optimal for the given relative values of p, e, and c, they are complex in nature, and would be difficult for a layperson to understand. Practical management often implies determining simpler, good but suboptimal policies that achieve the same objectives. These policies are often more desirable since they are easier to implement and easier to explain the rationale to the public.

As an example of suboptimal, approximate policies, the following nine modified base stock policies were examined:

Wood River

1) Base stock policy, base stock size = 0.84.
2) Policy of base stock size of 0.56 till 2.52, then a base stock size of 0.84.
3) Policy of base stock size of 0.56 till 1.40, then a base stock size of 0.84.
4) Harvest zero till 0.28, harvest 0.28 till 0.84, a base stock size of 0.56 till 2.52, then a base stock size of 0.84.

Branch River

5) Base stock policy, base stock size of 0.40

6) Base stock size of 0.4 till 1.6, then a base stock size of 0.6

7) Base stock size of 0.2 till 0.6, then a base stock size of 0.4

8) Base stock size of 0.2 till 1.0, then a base stock size of 0.4

9) Base stock size of 0.2 till 0.4, base stock size of 0.4 till 1.2, base stock size of 0.6 after that.

These nine approximate policies were devised by examining the functions that define the three regions in Figures 2 and 3. These approximate the boundaries of the three regions where the smoothing costs are ¼ to ½ the per unit value of the harvest. The mean per period harvest, variance, standard deviation, median per period harvest etc., for these nine policies are given in Table 2.

Policies 3 and 4 for the Wood River and 8 and 9 for the Branch River demonstrate how these approximate policies tend toward smoothing policies. For example, policy 4 has the same median harvest as the optimal base stock harvest, almost never closes the fishery, significantly decreases the percent of time there are low catches, and only reduces the mean per period harvest by 33,800 fish. In order to achieve a smoother catch, "potlatch" harvests from time to time have been sacrificed.

When looked at closely, these policies are actually very intuitive, and represent an interesting variant of a base stock policy. These policies replace a single base stock size by a dual base stock size

policy. The first base stock size is lower than the original one, while the second base stock size is greater than or equal to the original base stock size. This means that there are fewer states where there is no harvesting, but also lowers the likelihood of the really big harvests. The mean per period harvest tends to be very sensitive to these big harvests, while the median is not, particularly since the very large harvests are not too frequent.

It is curious that the population dynamics are so sensitive to such fine tuning, for the difference between policy 1 and policy 3, say, is quite marginal. It would be an interesting area of future research to determine guidelines for when fine tuning would be expected to produce such "trimming" of the tails of the ergodic distribution.

Including smoothing costs also tells us a great deal about traditional concepts of fisheries management, such as MSY. It is clear from Figures 2 and 3 that anything close to an MSY policy is optimal only if the smoothing costs exceed the per unit value of the harvest. As whole systems of laws for regulating fisheries have been constructed around the idea of smooth, constant harvests, it is clear that this imputes lower average catches, and a significant preference for constancy of the harvest over total amount harvested.

The analysis has assumed that equations (1.1) or similar equations are available, and that the parameter estimates are accurate (in this case, estimates of R_1, R_2, and σ^2). In the latter case, management measures would seem more reasonable if they were known to be robust

against misspecifying the parameters. This involves knowing how an optimal policy and total expected value would vary if the true underlying parameter values differ from those specified, and also how the estimate of the long-run probability distribution differs from the true one.

Van Hee (1977a) defines what he calls Bayesian equivalent returns. The transition probabilities used in this paper are derived from a regression model based on n observations, say. If another year's observation were available, we would expect the best estimates of the parameters to change. But as n gets large, we would also expect the parameters to begin to converge to the true
note 2 parameter values.[2] Suppose in each period, an optimal policy were calculated based on this period's best Bayes estimate of the parameters. Then next period, the Bayes estimate of the parameters are updated by including last periods observations, and again an optimal policy assuming these parameter values hold throughout is calculated. And so forth. This is a Bayes equivalent policy. Van Hee (1977a, theorem 3.1) proves that if the one-period return is separable into terms only depending on the state, and only depending on the decision, and the transition probabilities depend only on the decision (that is how large a population is left after harvesting has ceased), then a Bayes equivalent policy is optimal for the problem where full consideration is given period by period to the uncertainty in the parameter estimates.

This is an important result. It states that if we are only concerned with the best decision for this period for (1.2), then the policies presented are optimal, even if the parameters are misspecified. However, next period, the same computations would have to be redone for the new, updated parameter estimates. The one-period return that includes smoothing costs does not satisfy the conditions of van Hee's theorem, due to the term $-c \mid (x_t - y_t) - z \mid$. However, this model is so nearly separable, that it would seem likely that if a Bayes equivalent policy is not optimal, it should nearly be so.

No equivalent theorems exist for the effect on the long-run behavior of the system. Simple bounds do exist for estimating the value of an optimal policy for the full Bayesian model. To obtain a feel for these bounds, computations were performed for the Wood River with $R_2 = 0.6$, $R_2 = -1.0$, $\sigma = -0.35$, $\sigma = 0.55$, and for the Branch River with $R_2 = -1.5$, $R_2 = -2.0$, $\sigma = 0.48$, $\sigma = 0.68$. The
3 results are summarized in Table 3a. Suppose for the Wood River we believe R_2 lies on the interval (-0.6, -1.0). To get a rough idea of the value of an optimal Bayes policy, three distributions were analyzed. In the first, $R_2 = -0.6$, $R_2 = -0.8$, $R_2 = -1.0$ is assumed to be the true value with equal probability. The other two runs assign probabilities of ($\frac{1}{4}$, $\frac{1}{2}$, $\frac{1}{4}$) and ($\frac{1}{8}$, $\frac{3}{4}$, $\frac{1}{8}$). Van Hee (1977b) gives approximate formulas for the value of the Bayes optimal policy. These bounds were then compared with the values calculated for the runs assuming the present best estimate ($R_2 = -0.8$) is the

true value. The maximum deviation between these values over all states is given in Table 3. Similar calculations were performed for σ uncertain, and for the Branch River.

These results are interesting. In terms of the total expected discounted harvest, the value of an optimal policy using the present best estimate of σ is extremely close to the value of the Bayes optimal policy. All variations are well under 1% of the total value of the Bayes optimal policy. Uncertainty in our estimate of the variance of the random variable in (1.1) does not appear to be crucial for optimizing the total expected value. However, Table 3a suggests that the population dynamics are quite sensitive to variations in σ in terms of the tail probabilities of the ergodic distribution.

Uncertainty in the value of R_2 can cause changes in the actual value of an optimal policy by larger amounts (as compared to estimates using the present estimate of R_2 as the true value), but still the deviations are less than 4% of the total value when starting from any state. Moreover, Table 3a suggests that while the total value of the Bayes optimal policy will be reasonably different, the population dynamics, particularly in terms of tail probabilities of the ergodic distribution, are not sensitive to variations in R_2.

These results suggest that if (1.1) is the correct form of the model, then the model is robust to misspecification of the parameters. It should be reemphasized that the bounds compare the total value of an optimal Bayes policy with the total value from using the present estimates at all periods. Though Bayesian equivalent policies are

optimal for (1.2), they require making detailed observations each period, which can be costly. Table 3 suggests that the model is robust enough that detailed observations to update the parameter estimates can be made less frequently with little difference in total expected return, but with large savings to the company or agency responsible for obtaining the detailed observations.

SUMMARY

Uncertainty in fisheries management can be faced head on. Techniques exist that allow us to gain much insight into managing randomly varying populations. Optimization procedures allow us to reduce our attention to the few best policies, and analyze their properties, rather than pick policies ad hoc that meet no special criteria.

Optimization under uncertainty can also lead to a reconsideration of what is valued in managing a fishery--in the examples considered, some consistency in the amount harvested is a desirable alternative to high year-to-year fluctuations in the harvest size. But this reduces the average per period catch. Only in extreme situations, where the case of smoothing out the catch is greater than the unit value of the catch, does any policy resembling MSY become optimal.

Finally, it is possible to obtain an understanding of how robust the management measures are to misspecifications of the underlying model. This is important, since the model is only a guide to our decisionmaking, not THE ANSWER. In the models considered, the "best" policies are robust in view of this uncertainty.

A question not examined is the assumption that the population size is observed at the start of each period. This too is usually costly, and inexact. Recently, this author and Professor E. J. Sondik developed an efficient algorithm that addresses the relative merits of different sampling intervals for obtaining population estimates. Together, all of these techniques allow for an integrated, realistic approach to management under uncertainty.

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TEXT FOOTNOTE

[2]It is important to emphasize the difference between this convergence and that needed for deterministic models. For deterministic models to be useful, as more and more observations become available, the variance around the mean trend must decrease. For a stochastic model, it is not necessary the "fit" improve, only that the estimates of the parameters that determine the transistion probabilities converge to the true values.

Table 1.--Optimal policies for the different grid sizes.

Wood River	Grid size	Branch River
$y_t = \min(x_t, 0.9333)$	16	$y_t = \min(x_t, 0.3333)$
$y_t = \min(x_t, 0.840)$	26	$y_t = \min(x_t, 0.4000)$
$y_t = \min(x_t, 0.700)$	51	$y_t = \min(x_t, 0.3000)$
$y_t = \min(x_t, 0.770)$	101	$y_t = \min(x_t, 0.3500)$
$y_t = \min(x_t, 0.742)$	501	$y_t = \min(x_t, 0.3500)$
Equilibrium stock 0.735	Deterministic	Equilibrium stock 0.345

Table 2.--Vital statistics for the nine policies approximating the smoothing cost policies.

Policy	Mean per period harvest	Variance of per period harvest	Standard deviation	% time no catch	% time less than 25% of mean	% time greater than mean catch	Median catch	Relative value: smoothing/price
Wood River								
1	1.1357	0.8468	0.9202	5.6	16.8	39	0.98	0/1
2	1.0993	0.5460	0.7389	1.7	10.7	39.8	0.98	1/8
3	1.1203	0.6506	0.8066	1.1	7.7	43.2	0.91	1/4
4	1.1019	0.5758	0.7588	0.02	10.47	40	0.98	1/2
Branch River								
5	0.6528	0.3982	0.6310	9.2	21.8	40	0.500	0/1
6	0.6290	0.2532	0.5032	9.1	21.5	37.2	0.500	1/4
7	0.6272	0.3077	0.5547	1.2	27.7	31.3	0.400	1/2
8	0.5920	0.2202	0.4693	1.9	35.7	26.3	0.500	3/8
9	0.5995	0.3038	0.5512	0.72	22.83	39.3	0.500	3/4

Table 3a.--Trials with varied parameters.

River	Value of R_2	Value of σ	Optimal policy	Mean per period harvest	Variance	% time no harvest
Wood	-0.800	0.35	min (x_t, 0.7)	1.0680	0.390976	0.79
Wood	-0.800	0.55	min (x_t, 0.77)	1.2267	1.2422	7.8
Wood	-0.600	0.458	min (x_t, 0.980)	1.5108	1.3136	3.8
Wood	-1.000	0.458	min (x_t, 0.560)	0.9225	0.4839	3.29
Branch	-1.845	0.48	min (x_t, 0.35)	0.6122	0.2253	3.54
Branch	-1.845	0.68	min (x_t, 0.35)	--	--	--
Branch	-1.500	0.579	min (x_t, 0.40)	1.989	0.5254	5.82
Branch	-2.000	0.579	min (x_t, 0.30)	0.9075	0.3068	5.82

Table 3b.--Largest possible deviation in value of the approximate policy, compared to the true Bayes policy.

Probability distribution	When R_2 is uncertain			When σ is uncertain		
	$\frac{1}{3}, \frac{1}{3}, \frac{1}{3}$	$\frac{1}{4}, \frac{1}{2}, \frac{1}{4}$	$\frac{1}{8}, \frac{3}{4}, \frac{1}{8}$	$\frac{1}{3}, \frac{1}{3}, \frac{1}{3}$	$\frac{1}{4}, \frac{1}{2}, \frac{1}{4}$	$\frac{1}{8}, \frac{3}{4}, \frac{1}{8}$
Wood	1.4	0.51	0.5	0.04	0.03	0.03
Branch	1.04	0.47	0.38	0.01	$\leq$0.01	$\leq$0.01

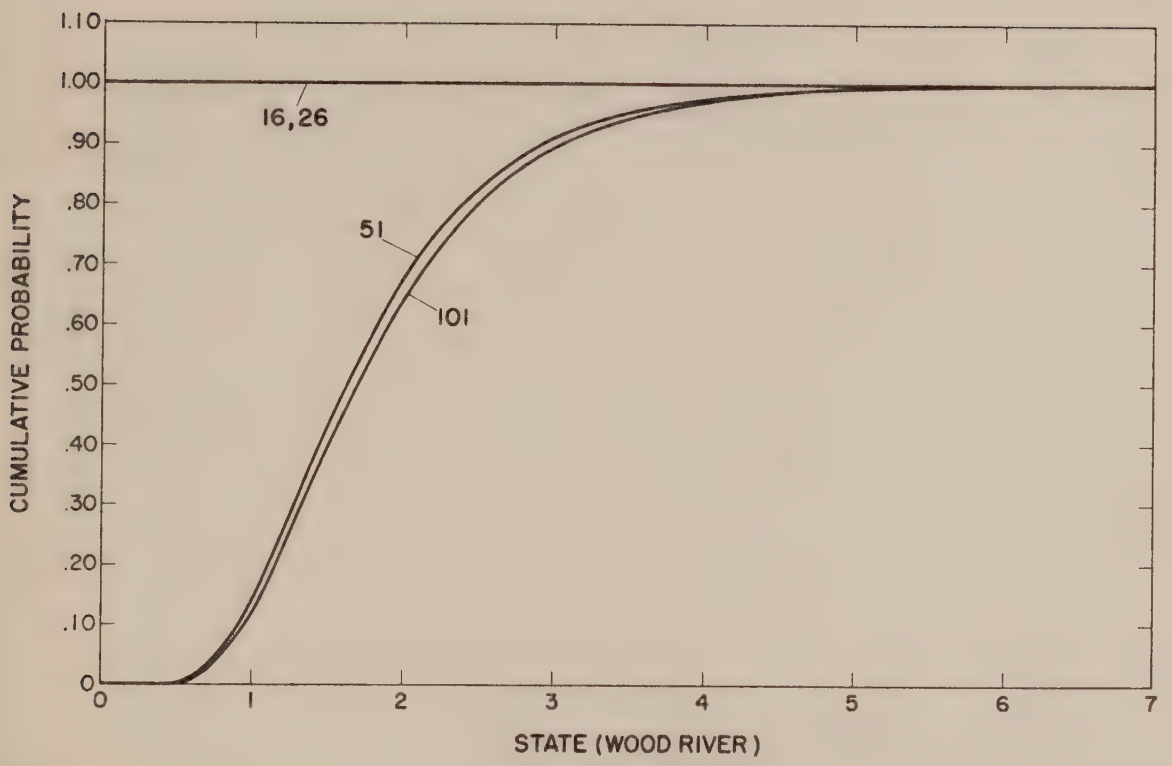

Figure 1(a).--Ergodic cumulative distribution for an optimal harvesting strategy for the Wood River, on grid sizes of 16, 26, 51, and 101 points.

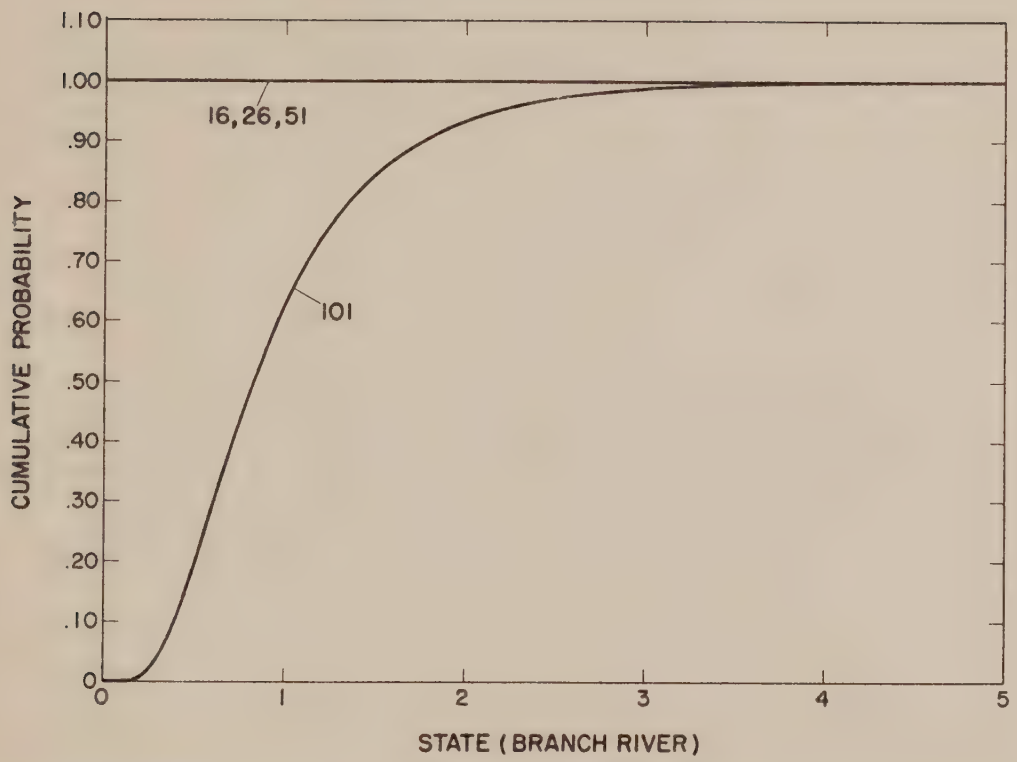

Figure 1(b).--Ergodic cumulative distribution for an optimal harvesting strategy for the Branch River, on grid sizes of 16, 26, 51, and 101 points.

Figure 2(a)-(m).--Optimal policy functions for the Wood River for various assumptions about the relative value of smoothing costs. (See text for details.)

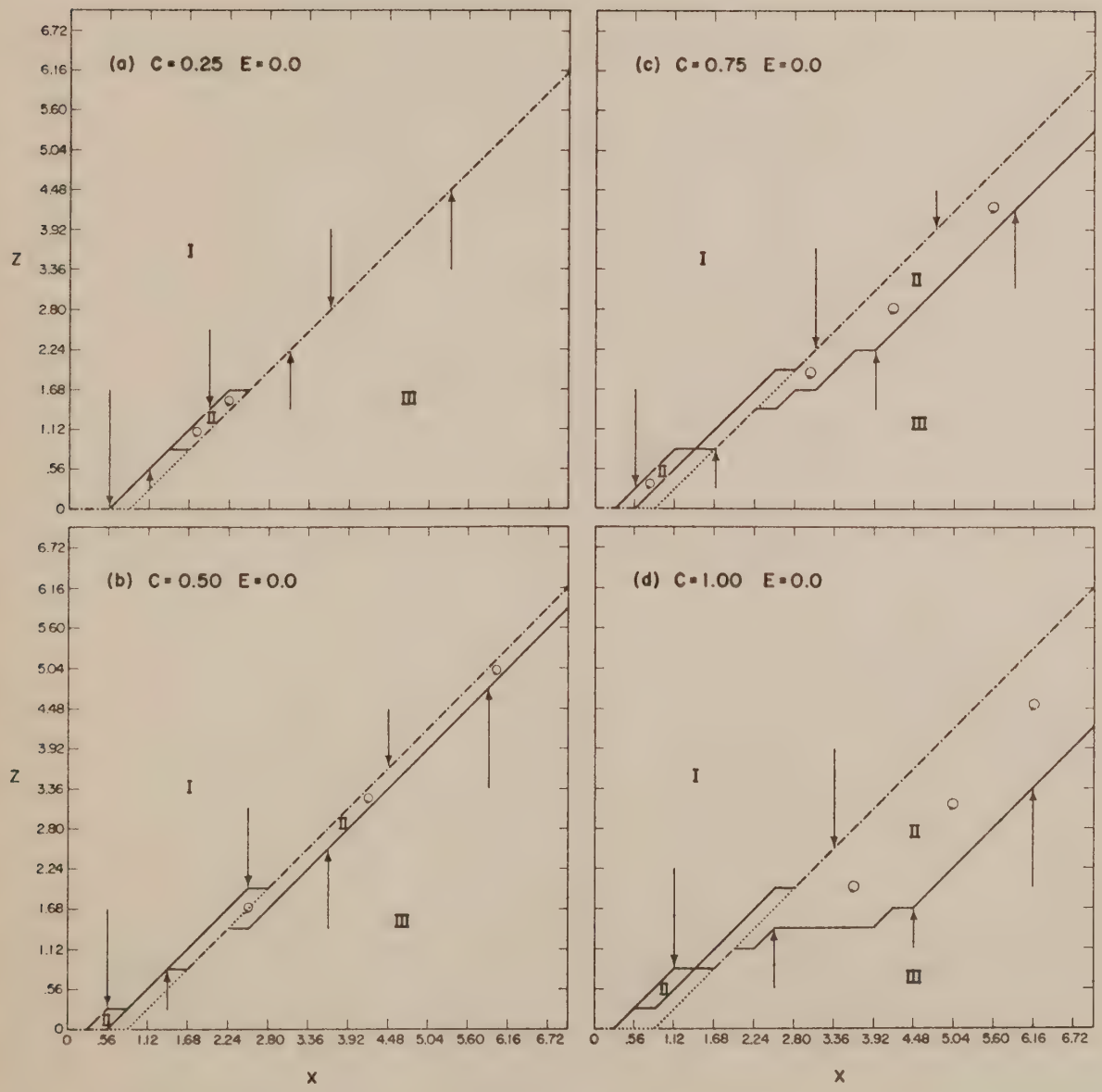
(a) C = 0.25 E = 0.0
(c) C = 0.75 E = 0.0
(b) C = 0.50 E = 0.0
(d) C = 1.00 E = 0.0
I
II
III
Z
X
0
.56
1.12
1.68
2.24
2.80
3.36
3.92
4.48
5.04
5.60
6.16
6.72

Figure 2

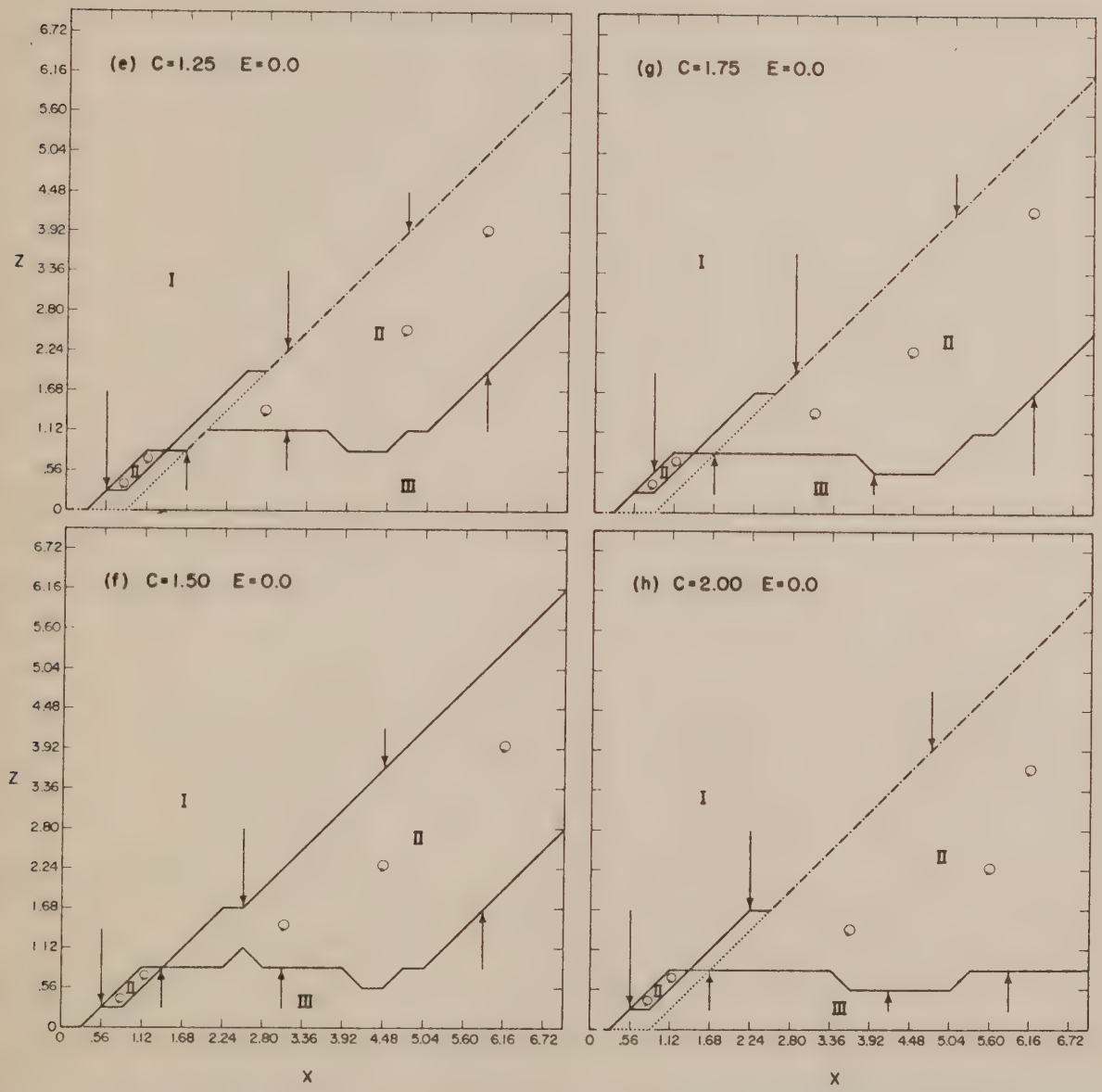

Figure 2.--Continued.

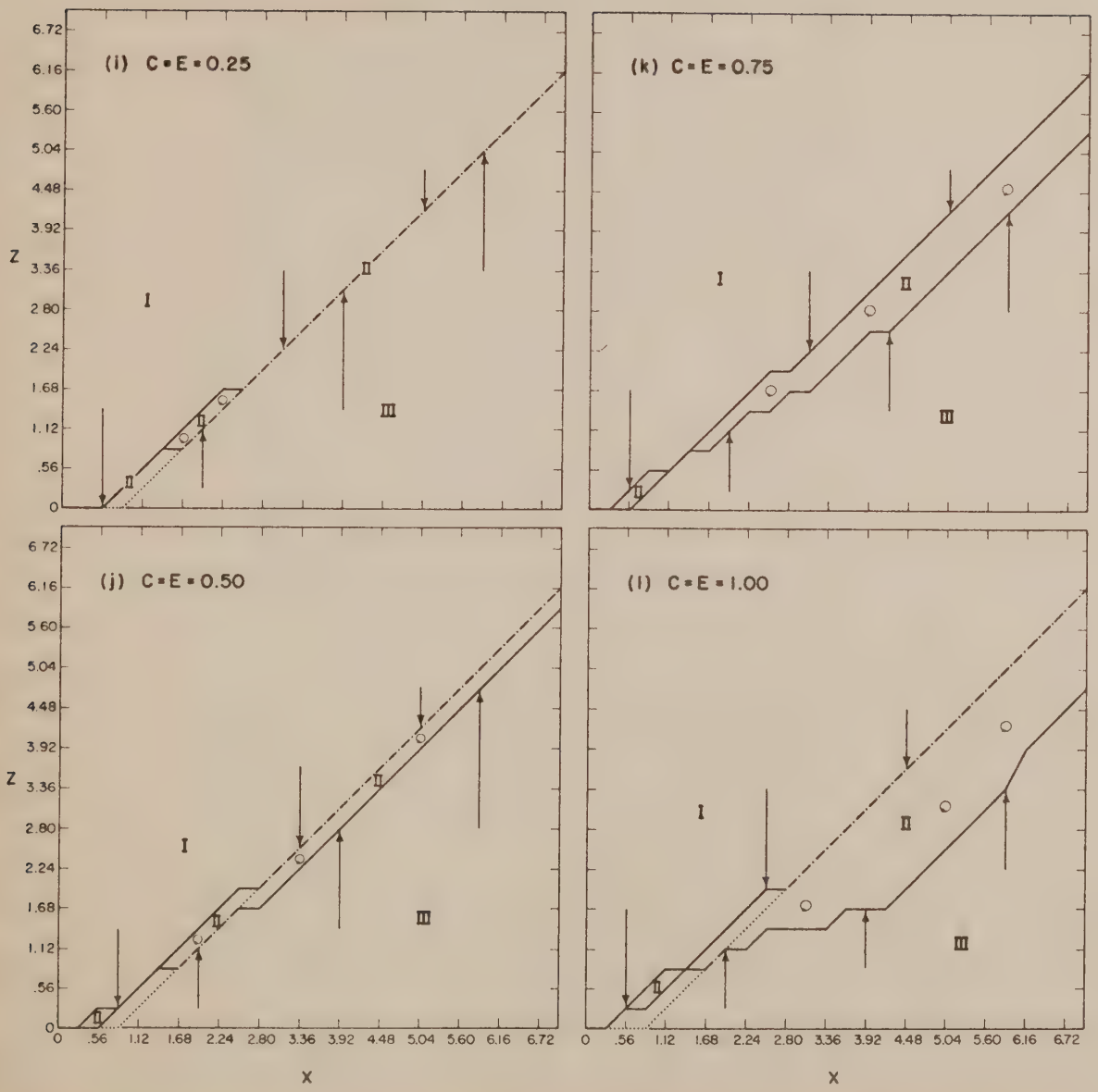

Figure 2.--Continued.

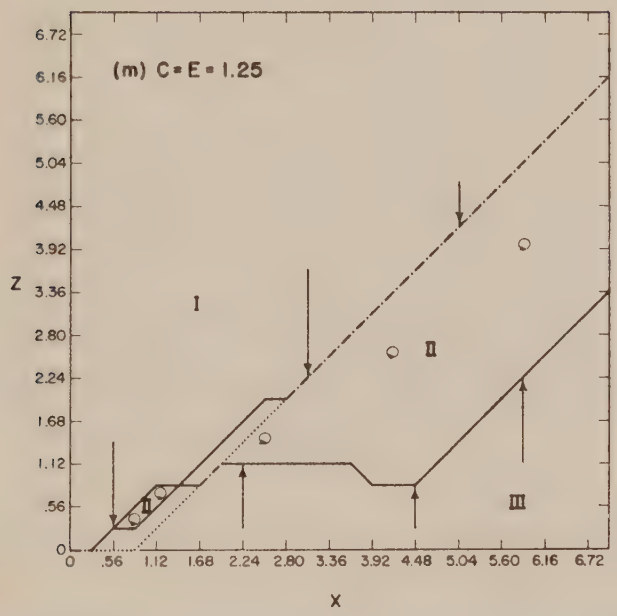

Figure 2.--Continued.

Figure 3(a)-(m).--Optimal policy functions for the Branch River for various assumptions about the relative value of smoothing costs. (See text for details.)

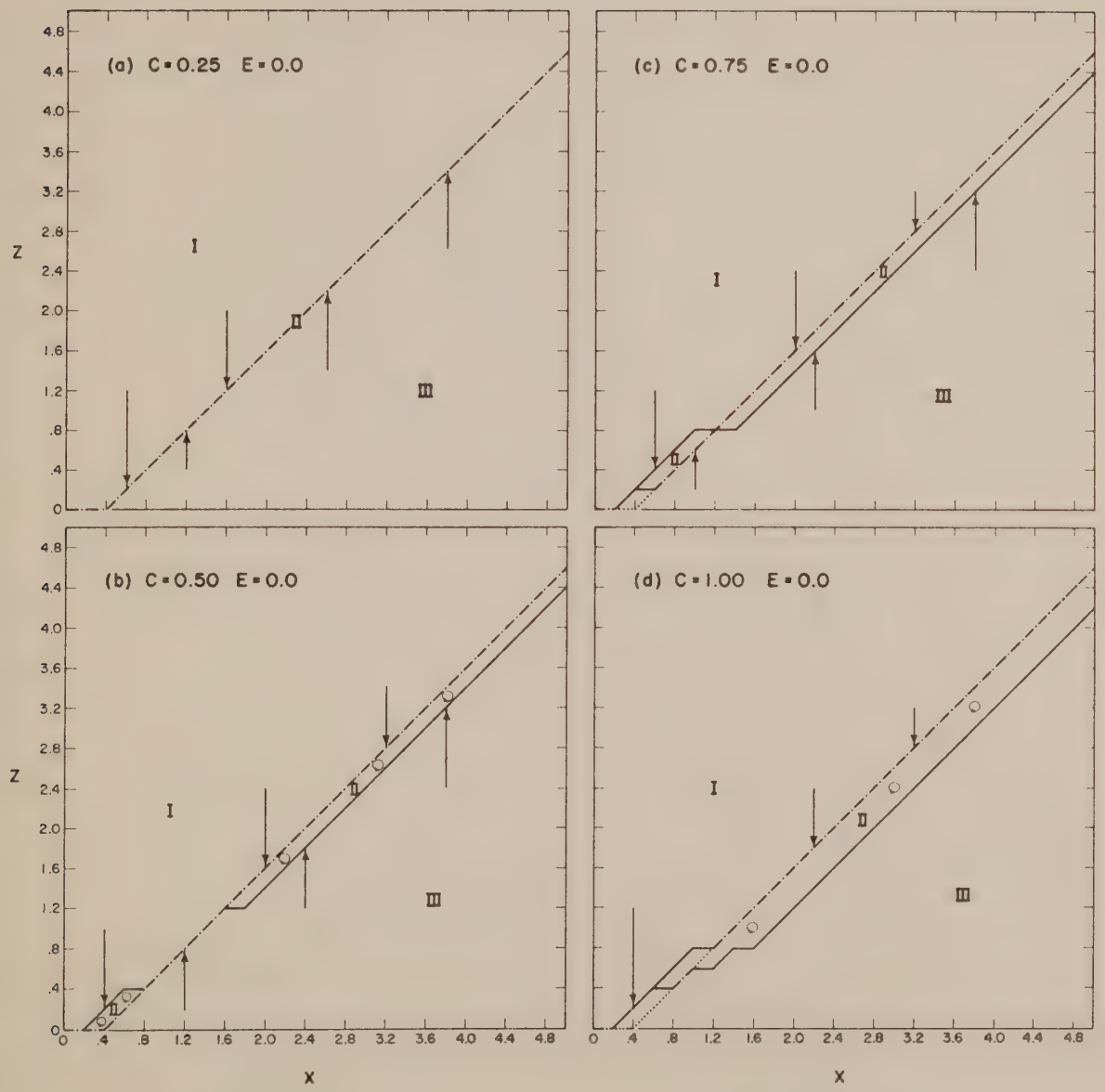
(a) C = 0.25 E = 0.0
(c) C = 0.75 E = 0.0
(b) C = 0.50 E = 0.0
(d) C = 1.00 E = 0.0
I
II
III
Z
X
0
.4
.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8

Figure 3

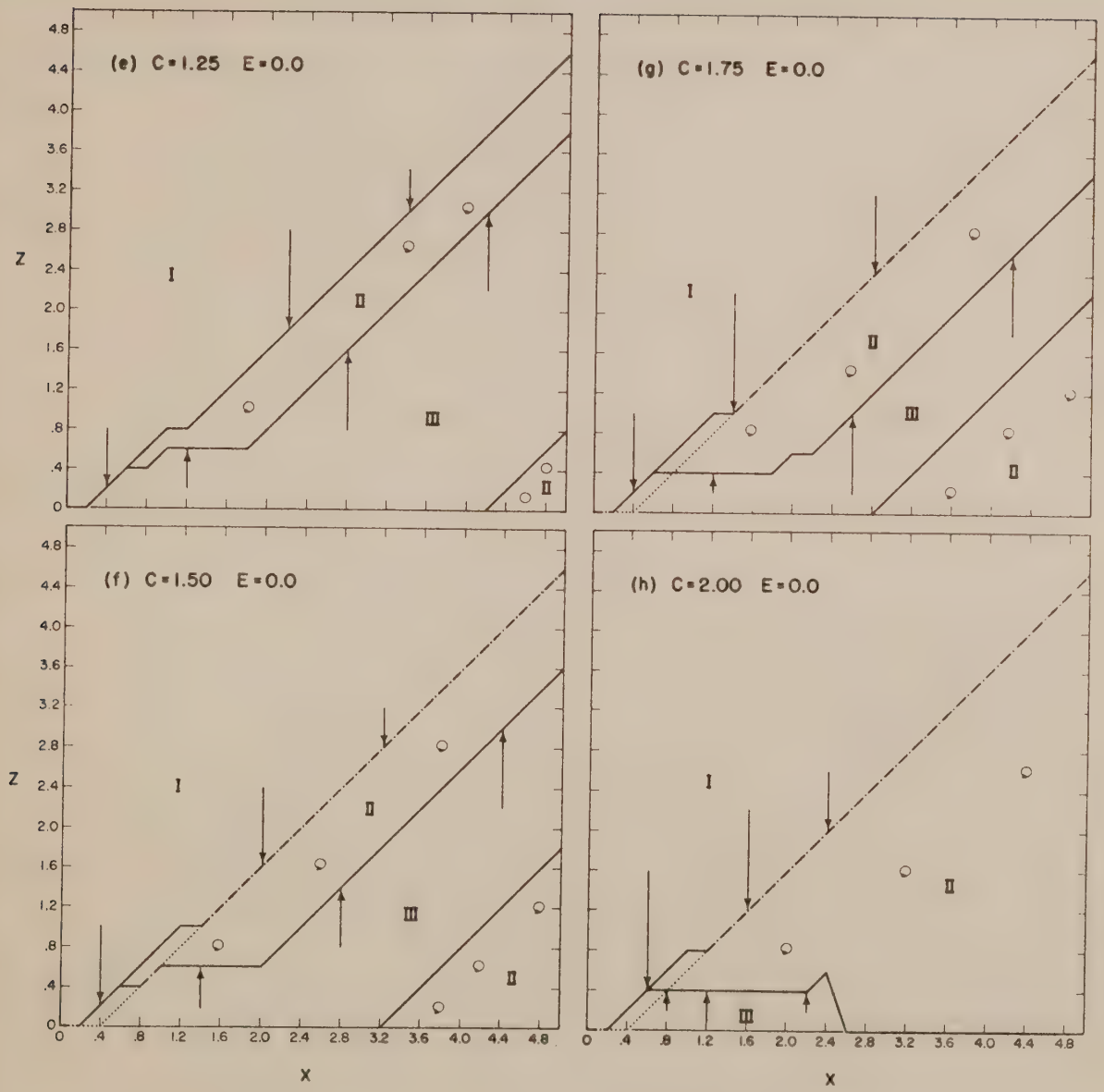

Figure 3.--Continued.

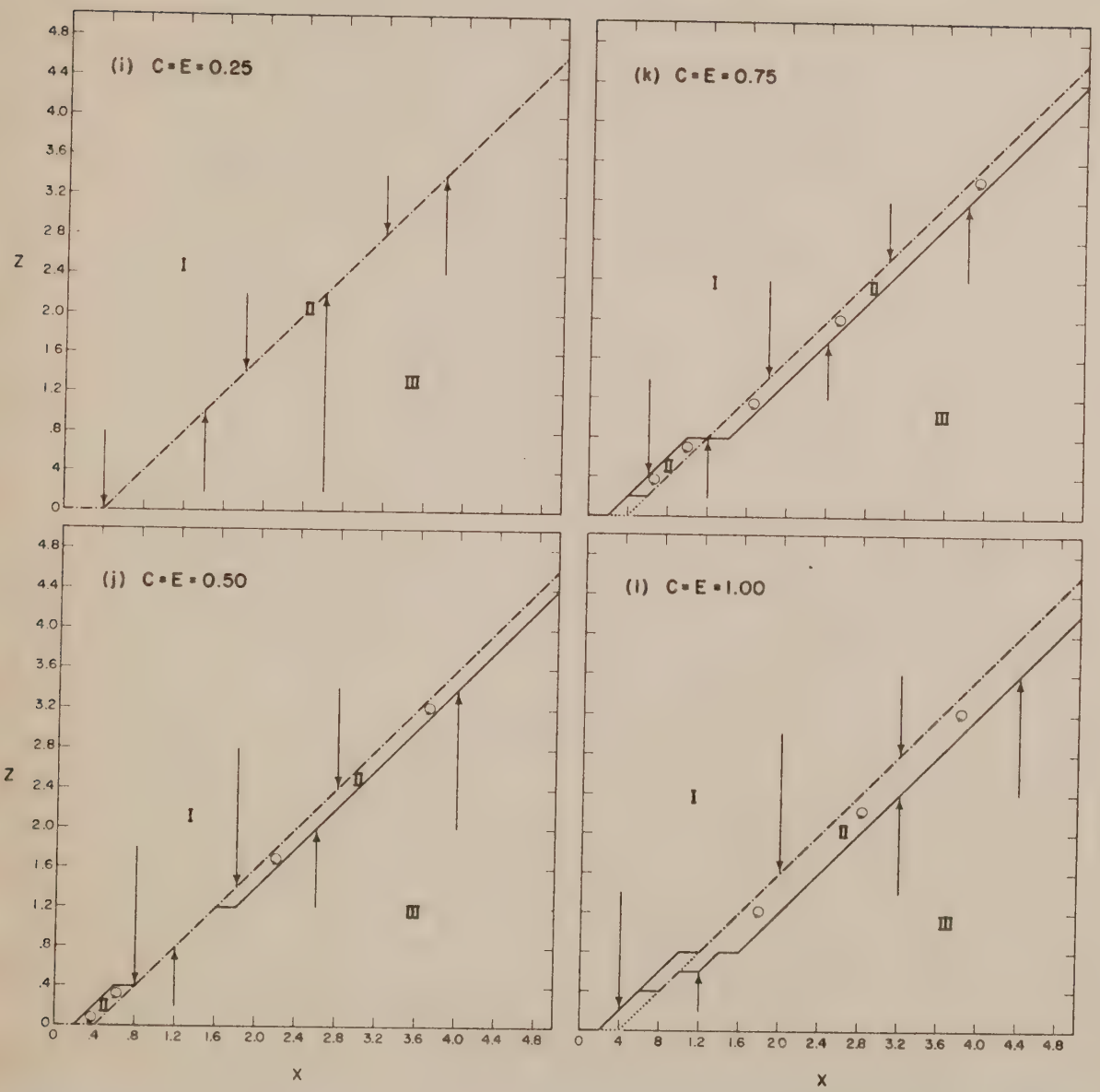

Figure 3.--Continued.

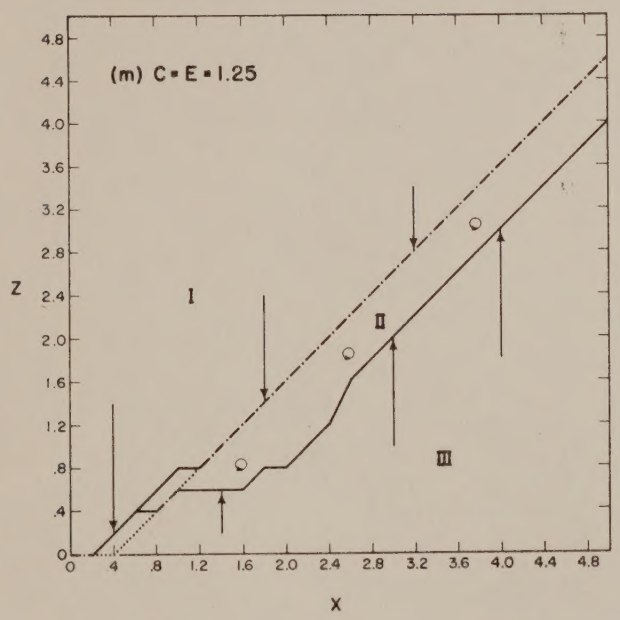

Figure 3.--Continued.